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Semantic-based discovery and integration of heterogeneous *things* in a Smart City environment

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To those who never give up.

"Science is but a perversion of itself unless it has as its ultimate goal the betterment of humanity."

Nikola Tesla

"All things appear and disappear because of the concurrence of causes and conditions. Nothing ever exists entirely alone; everything is in relation to everything else."

Siddhartha Gautama, Buddha

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Abstract

Title: ***Semantic-based discovery and integration of heterogeneous things in a Smart City environment***

A Smart City can be seen as a complex system in which different actors –such as people, governance, environment, living, mobility, and economy– cooperate in order to improve, the urban area, making it efficient and sustainable. To achieve this goal, the Information and Communication Technologies (ICT), and especially the prominent Internet of Things (IoT), are called to play a key role for implementing innovative solutions, services, and applications. However, looking at the current status, the realization of the Smart City is still far from being realized; the real scenario is indeed characterized with a high level of fragmentation due to the plethora of technologies and devices present in a city. In order to bridge this gap, in this thesis, the evolution of the Internet of Things -by using Semantic interoperability and Cloud computing- towards the Cloud of Things (CoT) is demonstrated. The CoT enables the horizontal integration of various (vertical) IoT platforms and applications, making therefore, feasible the realization of the Smart City vision. To demonstrate this concept, the VITAL operating system is introduced. Within the CoT, and in general in the Smart City context, one of the most important challenges is the discovery of appropriate data-sources that satisfy user requirements. The discovery is an operation that can be performed directly *in-network* (i.e., the detection of neighbors) and/or *out-network* (i.e., a middleware that aims to discover resources that belong to different networks). In this thesis, both processes are discussed by introducing two different solutions: the VITAL Internet Connected Objects & Services Discovery, which offers *out-network* functionality and CACHACA, a ranking mechanism for Sensor Networks that deals with *in-network* tasks. Going deeply towards a horizontal unification of different data-sources and the need to have processing capabilities closer to the network, in the last part of the dissertation, the design of a gateway for the Cloud of Things is introduced. This gateway is capable to discover and manage different semantic-like things and, on the other hand, to act as end-point for the presentation of data to users, bridging the contributions of this thesis. Moreover, thanks to the use of virtualized software, the gateway enables a lightweight and dense deployment of services.

Résumé

Titre : ***Pour une découverte et une intégration efficaces des choses dans une Ville intelligente***

Une ville intelligente peut être considérée comme un système complexe dans lequel les différents acteurs - tels que les personnes, la gouvernance, l'environnement, la vie, la mobilité et l'économie - coopérent afin d'améliorer la zone urbaine, la rendant plus efficace et plus durable. Pour atteindre cet objectif, les technologies de l'information et de la communication (TIC) et, en particulier l'Internet des Objets (IoT), sont appelées à jouer un rôle clé pour la mise en œuvre des solutions innovantes, des services et des applications. Cependant, en regardant l'état actuel de la ville intelligente, la réalisation d'un tel concept est encore loin d'être atteinte; le scénario réel est en effet caractérisé par un niveau élevé de fragmentation en raison de la pléthore de technologies et de dispositifs présents dans une ville. Afin de combler cette lacune, dans cette thèse, l'évolution de l'Internet des objets basée sur l'interopérabilité sémantique et le Cloud computing - vers le Cloud of Things (CoT) est démontrée. Le CoT permet l'intégration horizontale des différentes (verticale) plateformes et applications IoT, et rend donc possible la réalisation de la vision Smart City. Pour démontrer ce concept, le système d'exploitation VITAL est introduit. Dans le CoT, et en général dans le contexte Smart City, l'un des défis les plus importants est la découverte de données-sources appropriées aux besoins des utilisateurs. Cette découverte est une opération qui peut être exécutée directement *in-network* (par exemple, la détection des voisins) et / ou *out-network* (par exemple, un intergiciel qui vise à découvrir des ressources qui appartiennent à des réseaux différents). Dans cette thèse, les deux processus sont discutés en introduisant deux solutions différentes : le VITAL ICO & Services Discovery, qui offre des fonctionnalités *out-network* et CACHACA, un mécanisme de classement pour les réseaux de capteurs adapté aux faibles ressources matérielles des objets qui traite des tâches *in-network*. En ce qui concerne la découverte in-network, dans la dernière partie de la thèse, la conception d'une passerelle pour le Cloud of Things est introduite. Cette passerelle est capable de découvrir et de gérer différents objets sur une base sémantique et, d'autre part, d'agir comme point final pour la présentation des données aux utilisateurs, combinant ainsi tous les aspects de cette thèse. En outre, grâce à l'utilisation du logiciel virtualisé, la passerelle permet un déploiement léger et dense de services.

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List of Abbreviations

CACHACA	Confident-based Adaptable Connected objects discovery to HArmonize smart City Applications
CEP	Complex Event Processing
CoAP	Constrained Application Protocol
CoT	Cloud of Things
DaaS	Data as a Service
DMS	Data Management Services
ETSI	European Telecommunications Standards Institute
FIT	Future Internet of Things
GPRS	General Packet Radio Service
GPS	Global Positioning System
IaaS	Infrastructure as a Service
ICO	Internet-Connected Object
ICT	Information and Communication Technologies
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IoE	Internet of Everything
IoT	Internet of Things
IT	Information Technology
ITU	International Telecommunication Union
JSON	JavaScript Object Notation
JSON-LD	JavaScript Object Notation Linked Data
HTTP	Hypertext Transfer Protocol
NaaS	Network as a Service
NFC	Near Field Communication
NT	Neighbor Table
OWL	Web Ontology Language
PaaS	Platform as a Service
PADA	Platforms Access and Data Acquisition
PoI	Point of Interest
PPI	Platform Provider Interface
RDF	Resource Description Framework
RFID	Radio Frequency Identification
RSSI	Received Signal Strength Indication
SaaS	Software as a Service
SeaS	Sensing as a Service
SD	ICO & Services Discovery

SN	Sensor Network
SSN	Semantic Sensor Network
SPARQL	SPARQL Protocol and RDF Query Language
UMTS	Universal Mobile Telecommunications Service
URI	Uniform Resource Identifier
URL	Uniform Resource Locator
URN	Uniform Resource Name
VITAL	Virtualized programmable InTerfAces for innovative cost-effective IoT depLoyments in smart cities
VUAI	Virtualized Universal Access Interfaces
WiMAX	Worldwide Interoperability for Microwave Access
WSN	Wireless Sensor Network
W3C	World Wide Web Consortium
XaaS	Everything as a Service
XML	eXtensible Markup Language

Chapter 1

Introduction

1.1 Towards a *Smarter* City

The town development, from the Greece's "polis", the roman's "urbis", the renaissances cities like "Florence", signs major milestones in our civilization history, up to the contemporary, global metropolis, where advanced services have replaced industrial plants [105].

During this evolution, the city has always been the core of aggregation and socialization, where trade, art, culture, and (lately) technology can help in designing and building solutions to many issues -i.e., environmental climate change and pollution, unemployment, fossil energy, etc.-.

With the onset of the agricultural and industrial revolution (late 18th century), people started to move from rural to urban areas in order to access major opportunities for jobs, education, housing, and transportation. In England, for example, the percentage of the population living in urban areas jumped from 17 % in 1801 to 72 % in 1891 [112].

Following this trend, in 2010, 50 % of the world's population was living in cities [50]; in the developed world the proportion of people living in cities is higher than 75 %. In China, even though the proportion of people living in cities is under 50 % (Figure 1.1 [115]), the total number of urban dwellers is the greatest (559 million).

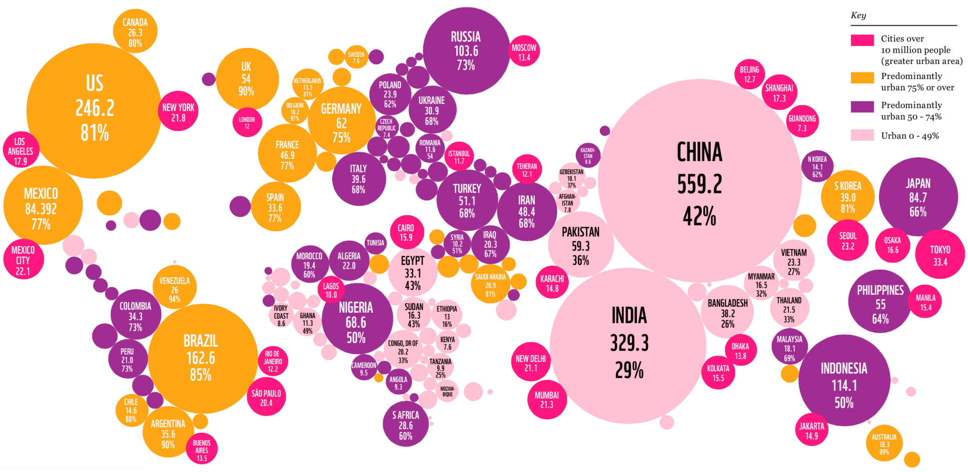

FIGURE 1.1: Number of people together with percentage of population living in cities in each country in 2010.

Fast Co. Design [27] forecasts that in 2050, 70 % of the world's population will be urban. It is, therefore, crucial for cities to become *"smarter"*, in order to be ready to accommodate this huge amount of citizens and to face new arduous challenges (e.g., traffic congestion, air pollution, waste management, water monitoring, and so on).

In this context, in the early 1990s, the phrase "Smart City" was coined to describe the evolution of the urban development towards technology, innovation and globalization [32], highlighting on the need of *"smarter"* urban ecosystems. Since then, the concept starts to gain popularity and to be used all over the world with different names and in different circumstances. Nam et al., in [68], grouped those initiatives in three different dimensions (Table 1.1): *technology*, *people*, and *community*.

From a technology perspective:

- a *Digital City* is defined as "a virtual environment that administers others -in either the private or public sector- where both marketing and social aspects must support public benefit" [3]. In [53], a Digital City is defined as "an arena in which people in regional communities can interact and share knowledge, experiences, and mutual interests".

- the notion of *Intelligent City* refers to "a city that has all the infrastructure and info-structure of information technology, the latest technology in telecommunications, electronics, and mechanical technology" [60].

- a *Ubiquitous City* is "an extension of Digital City concept in terms of ubiquitous accessibility and infrastructure" [4].

- an *Information City* refers to "digital environments collecting information from local communities and delivering it to the public via web portals" [14].

Regarding the people perspective, variants are: the *Creative City* -a city that has human infrastructures as epicenter (i.e., crime-free environments, voluntary organizations, knowledge networks, creative occupations and workforce) [29]- and the *Learning City*, which is actively involved in building a skilled information economy workforce [91].

The *Smart Community* concept, in the community perspective, is a "community in which government, business, and residents understand the potential of information technology, and make a conscious decision to use that technology to transform life an work in their region in significant and positive ways" [51].

Aloi et al., in [2], classified the requirements for Smart City in two different types:

1. *Service/application*, considered from the point of view of the citizens.

TABLE 1.1: Smart City - conceptual variants [68].

Dimension	Concept	Reference
Technology	Digital City	[3, 116, 53]
	Intelligent City	[54, 60]
	Ubiquitous City	[4]
	Information City	[14]
People	Creative City	[29, 57]
	Learning City	[91]
Community	Smart Community	[51]

2. *Operational*, seen from the city authorities and network administrators viewpoint.

Concerning the *service/application* aspects, the end-user devices equipped with multiple radio technologies and several sensors and actuators deployed all over the cities, make possible the individuation of novel services and applications for the citizens. These services will have specific features, like: *i)* **user-centric**: based on the specific context and the preferences of the users, *ii)* **ubiquitous**: reachable everywhere and from any devices, and *iii)* **highly-integrated**: based on the integration of services and data from several and different applications or on the social cooperation of multiple users. Of course, beyond the citizens, also the stakeholders of a city, like educational institutions, health-care and public safety providers, governmental organizations, etc. will be in conditions to exploit the key features of these new services that make the city more sustainable.

On the other hand, the Smart City concept considered from the point of view of the *administrations and network providers* is translated into a network infrastructure that is: *i)* **highly-interconnected**: by overcoming the heterogeneity of the devices it is possible to provide ubiquitous connectivity, *ii)* **cost-efficient**: the deployment and organization of the network should be as much automatic as possible and independent from the human intervention, *iii)* **energy-efficient**, able to realize an efficient resource utilization, in order to meet the main requirements of *green* applications, and *iv)* **reliable**: the ubiquity of the network should be guaranteed above all in the case of exceptional and adverse conditions. The real scenario we can observe nowadays is, anyway, characterized with a high level of *fragmentation* of technologies, lack of ubiquity in terms of both connectivity and coverage, due to the plethora of technologies and devices present in a city environment. This *fragmentation* is mainly due to the presence of many access networks usually managed by different operators -i.e. Universal Mobile Telecommunications System (UMTS), Worldwide Interoperability for Microwave Access (WiMAX), WiFi, etc.-.

The aforementioned concepts emphasize on the human and social aspects. The "Smart City" concept cannot be seen, indeed, just as a technological solution; it involves and integrates different actors such as people, governance, economy, living, environment, and mobility (Figure 1.2).

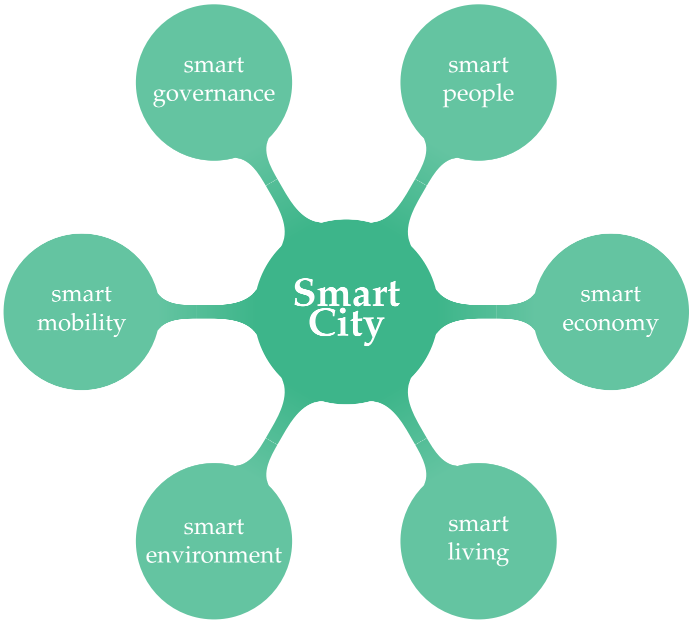

FIGURE 1.2: Smart City domains.

Many definitions of Smart City have been introduced in literature highlighting on the need of integration among the different city's infrastructures. Table 1.2 summarizes some of most in vogue [38, 40, 105, 39, 61] in which the role of *intelligent devices*, and in general Information and Communication Technologies (ICT), is crucial in order to harmonize the city environment and to implement innovative solutions, services, and applications [9].

To confirm this vision also big companies, like IBM, consider a Smart City as a complex infrastructure of *"System of Systems"* in which each individual system is an amalgamation of public and private sector organizations that span multiple industries [55]. For example, the *Smart Mobility* system -for moving people and goods from place to place- involves a number of industries -such as automotive, railways, travel, aerospace, logistics providers, energy and petroleum- and virtually every level of government, from city councils to national transport authorities.

In the same direction, also Cisco, with the *Internet of Everything* (IoE) [64], aims at the creation of a *network of networks* where billions or even trillions of connections create unprecedented opportunities.

In this context, the Internet of Things (IoT) [5] paradigm will play a primary role as an enabler of a broad range of applications, for both industries and general population. Figure 1.3 shows the Libelium Smart World full of sensors -which helps to improve humans lifestyle- and machines -which talk to other machines on their own- [58]. As a result, disparate applications

TABLE 1.2: Some of the Smart City definitions.

Authors	Definition
[38]	A city that monitors and integrates conditions of all of its critical infrastructures.
[40]	A city that connects the physical infrastructure, the IT infrastructure, the social infrastructure, and the business infrastructure to leverage the collective intelligence.
[105]	A city that combines ICT and WEB 2.0 technology with other organizational, design and planning efforts, to de-materialize and speedup bureaucratic processes and help to identify new, innovative solutions to city management complexity, in order to improve sustainability and livability.
[39]	A city that functions in a sustainable and intelligent way, by integrating all its infrastructures and services into a cohesive whole and using intelligent devices for monitoring and control, to ensure sustainability and efficiency.
[61]	A city seeking to address public issues via ICT-based solutions on the basis of a multi-stakeholder, municipally based partnership.

will be available in order to create smart roads, smart parking, noise urban maps, traffic congestion, smart lighting, and so forth.

1.2 Contributions of this thesis

The role of the Internet of Things will be crucial in the development of future Smart Cities. At the same time, it is also evident that the IoT applications nowadays available are standalone, based on different standards and protocols, going against those needs of integration, cooperation, and interoperability required between the Smart City stakeholders. Those are the challenges that the FP7 VITAL[1] project -which funded this work- aims to address. VITAL is an Internet of Things architecture that enables the development, deployment, and operation of semantically interoperable applications for Smart Cities.

In this Thesis we address the following questions:

1. *"Is the IoT enough to realize the Smart City vision?"* As it is nowadays, the IoT is not adequate to enable the complete Smart City vision. There is indeed, a need to bridge the gap between the different IoT ecosystems. Therefore, the first contribution of this Thesis regards the evolution of the Internet of Things towards the Cloud of Things (CoT). This

[1] http://vital-iot.eu

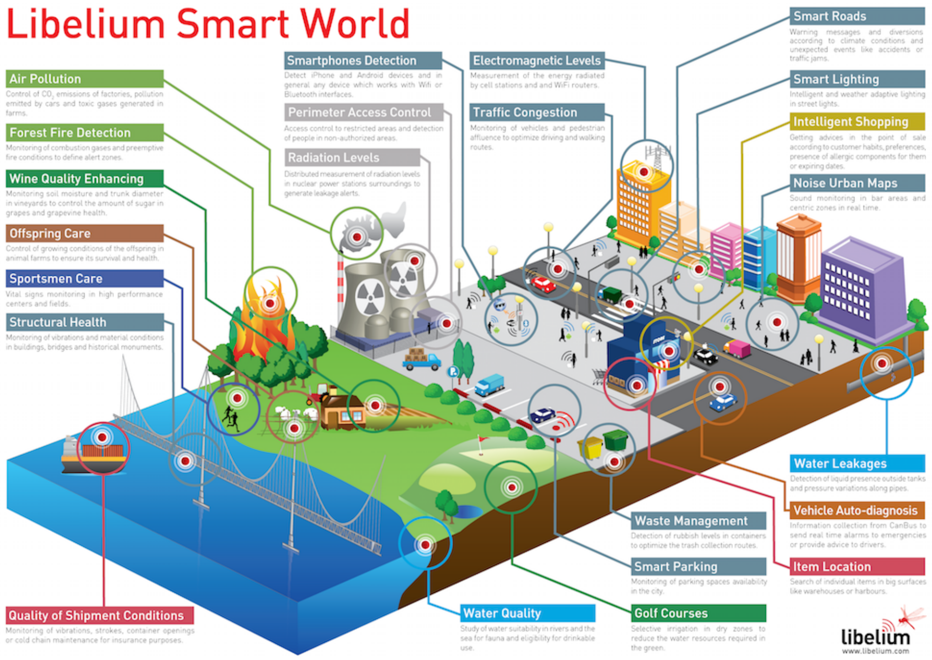

FIGURE 1.3: Libelium Smart World vision [58].

progress is possible thanks to Semantic technologies -well recognized as good enablers in the complex process of integration of heterogeneous data-sources- and Cloud computing -which assures scalability, availability, and so forth-. To validate the proposal, the VITAL operating system for Smart City is introduced as a solution that embraces the CoT philosophy.

2. *"How to discover data-sources that better suit business criteria?"* One of the most important challenges within the CoT context and the Smart City in general, is the discovery of appropriate data-sources that satisfy user requirements. It is indeed, important to have mechanisms capable to provide, in an efficient way, resources that better suit business criteria defined by users. To deal with this challenge, in this Dissertation we propose two complementary mechanisms, the *VITAL ICOs & Services Discovery* and *CHACACA* (Confident-based Adaptable Connected objects discovery to HArmonize smart City Applications). The first one is a module of the VITAL's architecture that is responsible for discovering Internet-Connected Objects, Systems, and Services. The second one, is a mechanism that deals with *in-network* tasks. It offers means to discover and to evaluate the services provided by each network element by leveraging on the flexibility of fuzzy logic. CACHACA has been first evaluated through simulations and then stressed when facing a realistic environment through experimentation run on the FIT IoT-lab testbed. Achieved results demonstrate its effectiveness in the discovery of process.

3. *"How to connect heterogeneous devices to the Internet and, at the same time,*

bring processing closer to the data-source?" With the increasing number of available technologies in the IoT landscape, it is important to have devices capable to present those *things* to consumer applications and users. In the last part of the Thesis, the design of a gateway for the Cloud of Things is proposed. The gateway can deal with different IoT scenarios and technologies and thanks to emerging virtualization techniques, it guarantees a lightweight and dense deployment of services. The gateway is designed to discover and manage different semantic-like things and, and to act as end-point for the presentation of data to users, bridging the contributions of this Thesis.

By answering to the aforementioned questions, in this Thesis, we offer technological tools capable to deal with Smart City scenarios at different layers. We firstly introduce a whole system (VITAL) designed to act as operating system for urban environments. Then, we address the challenge of discovering appropriate data-sources -which satisfy user requirements- in a complex context, such as a Smart City, by introducing two complementary mechanisms that deal with *out-* and *in-network* tasks. Those contributions are bridged by introducing a gateway designed to unify different data-sources and, on the other hand, to act as end-point for the presentation of data to users.

1.3 Structure of the thesis

The Thesis is organized as follows:

- Chapter 2 presents the state of the art and the reason behind the massive attention received by the Smart City paradigm while highlighting the key role played by the Internet of Things in the context.

- Chapter 3 is dedicated to the evolution -by using Semantic technologies and Cloud computing- of the Internet of Things towards the Cloud of Things. To validate this vision, the VITAL operating system for Smart City is introduced.

- Chapter 4 focuses on the challenge of discovering appropriate data-sources in a complex scenario like the one of Smart Cities. Two complementary mechanisms will be presented, the VITAL ICOs & Services Discovery that aims to address *out-network* problematic and CACHACA, a ranking mechanism for Sensor Networks that deals with *in-network* tasks.

- Chapter 5 introduces the design of a gateway for the Cloud of Things. The gateway is able to manage semantic-like things and to act as end-point for the dynamic presentation of real world data to consumer applications and users. In order to deal with different scenarios and technologies, the gateway is modeled to guarantee a lightweight and dense deployment of services, by leveraging on the emerging virtualization techniques,

- Chapter 6 concludes the Thesis and draws the future guidelines in order to improve the solutions proposed.

Chapter 2

State of the art

The continuous growth of the urban population has generated a drastic expansion of our cities. Nowadays, more than 50 % of the world's population is urban, and they forecast that it will reach 70 % by 2050 [27]. It is therefore important to make cities ready to accommodate this huge amount of citizens and to improve the quality of life by facing new challenges such as traffic congestion, air pollution, waste management, etc.

In this context, Information and Communication Technologies, and especially the Internet of Things, are called to play a crucial role. This Chapter highlights on the benefits and limitations of the IoT in the realization of the Smart City vision.

Moreover, we shows the current status towards the realization of the Smart City by introducing some pilots and European initiatives.

2.1 The Internet of Things

"The Internet of things has the potential to change the world, just as the Internet did. Maybe even more so." [5]. With this sentence, in 1999, Kevin Ashton introduced for the first time the term of "Internet of Things" (IoT). Some years later, in 2005, the International Telecommunication Union (ITU), formally defined the IoT as a technology capable to *connect **anyone**, from **anyplace** and **anytime** to **anythings*** [52]. Since then, the IoT starts to attract the attention of both academia and industry; its capability to create a world where all the *objects* around us are connected together and to the Internet with minimum human intervention, makes, indeed, possible the development of a huge number of applications in different domains.

2.1.1 Technologies

Different technologies are available to connect objects already well spread in our everyday life environment like RFID in subway, 4G with our phone, Wi-Fi for Internet at home etc. Below, some of the most representative technologies are presented.

Sensors represent an essential component of any intelligent control system. Thanks to technology advances, a multitude of different sensors is nowadays available, enabling applications that were unimaginable in the past. Sensor nodes are usually scattered in a sensor field; each of these scattered sensor nodes has the capability to collect data and route it back to a special node called "sink" by a multihop infrastructure-less architecture [1]. Currently, most of commercial Wireless Sensor Networks (WSN) are based on the IEEE 802.15.4 standard [49], which defines the physical and MAC layers for low-power, low bit-rate communications in wireless personal area networks (WPAN). However, IEEE 802.15.4 does not include specifications on the higher layers of the protocol stack, which are necessary for the integration of sensor nodes into the Internet [6]. The role of Sensor Network (SN) in the IoT is crucial and well examined in [76].

Smartphones represent another interesting sensing scenario. Indeed, the ever increasing number and the presence of a mixture of sensors such as GPS, gyroscopes, accelerometers and compasses, enabling a variety of crowd sourcing applications, which will eventually be augmented by the IoT. For instance, as users regularly update their location status on social networks like Twitter and Facebook; based on this location information, it is possible to aggregate this data, enabling tasks to be dispatched to people in specific locations [39].

Regarding to short range communications, two interesting technologies in the IoT context are Radio Frequency Identification (RFID) and Near Field Communication (NFC).

RFID is a method of identifying unique items using radio waves. Typical RFID systems are made up of 2 major components: readers and tags. The reader sends and receives RF data to and from the tag via antennas. The tag is made up of a microchip that stores data, an antenna, and a carrier to which the chip and antenna are mounted [98]. RFID can be used to develop a large number of applications, to name a few: smart parking [71], traffic monitoring [74], library management [93], transportation tickets, etc.

NFC is a contactless wireless communication technology based on RFID and Internet technologies [111]. It supports the communication within 20 centimeters, and it represents a prominent technology, enabling a range of applications in order to make people's life more convenient and fast, i.e. the digital wallet introduced in [7] or building access control.

Integrating resource-constrained devices into the Internet is difficult since ubiquitously deployed Internet protocols such as HTTP, TCP, or even IP are too complex and resource-demanding [89]. Many initiatives have been proposed in literature; here below some of the most relevant.

The μIP [22] includes a low-power link built on IEEE 802.15.4 for small embedded devices. 6LoWPAN [56] defines mechanisms capable to fragment and to compress the header of IPv6 datagrams. Hui et al. in [48] consider multiple WSNs connected by IPv6-based *border routers* through IP links, including Ethernet, Wi-Fi, GPRS, and satellites.

Constrained Application Protocol (CoAP) [19] is an application layer protocol designed for energy constrained devices. It deals with Constrained

RESTful environments, providing a lightweight alternative to HTTP. CoAP and 6LoWPAN allow sensor nodes to be integrated into the web, through the use of proxies for HTTP to CoAP conversion.

As seen, a lot of effort has be done in order to design intelligent devices that can be adopted to improve our daily life. At the same time, the need to integrate those resource-constrained objects to the Internet -and the possibility to remotely manage them- is evident and important in order to implement more complete, accurate, and useful applications.

2.1.2 Applications

Figure 2.1 shows some of the main IoT application domains, i.e., smart metering, home automation, smart agriculture, eHealth, retail, etc.

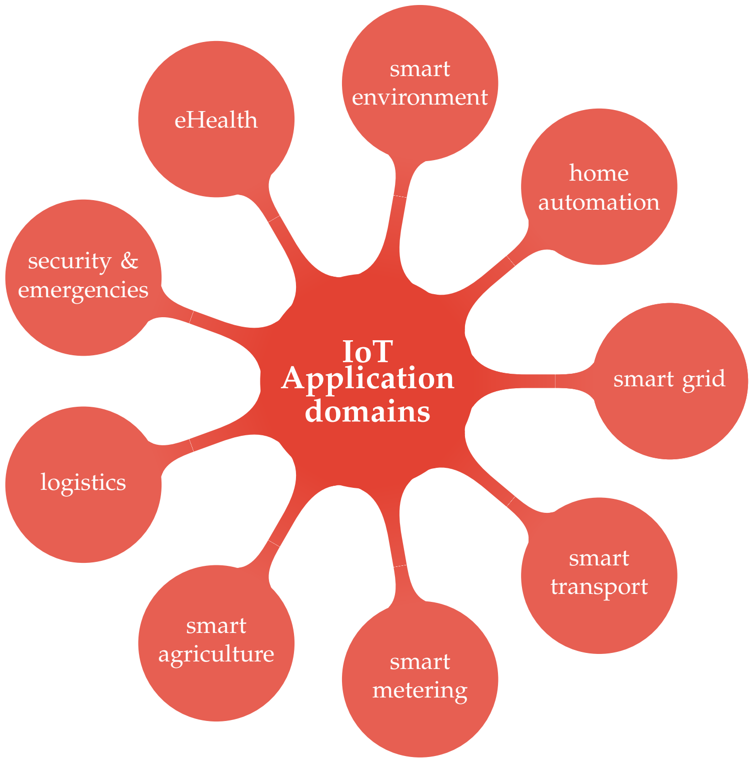

FIGURE 2.1: IoT application domains.

Smart Transport is one the hot application within the Smart City context. Due to the increasing number in cars number over recent years, there is an urgent need to improve the traffic management, by avoiding traffic jams and optimizing traffic flow.

Smart Environment and in general environmental monitoring is absolutely important in order to ensure, and improve, the quality of life. By monitoring the quality of water and air, and other parameters such as ambient carbon dioxide level, temperature, humidity, etc. we can, indeed, keep the pollution to an acceptable level. In order to empower smart environments, it is necessary to collect data from different sensors. In this context, thanks to the diffusion of smartphones, it is possible to create collaborative environment monitoring, like for example "SoundCity"[1], a mobile application for understanding the exposure to noise pollution.

Smart Grid is another prominent application in the Smart City landscape, thanks to its objective to reduce carbon emission resulting from energy generation and consumption. Conventional electricity grid has been developed based on the assumption that electricity is generated at few stations generally outside urban areas and transported and distributed to large, medium and small sized consumers. The grid is nowadays, evolving to a power network combined with large central power plants. Electricity can be generated, consumed and stored anywhere in the grid. Renewable energy sources offer pollution free, climate friendly, sustainable and unlimited sources of energy. Their integration into the power grid is driven largely by environmental and economic regulation aimed at transforming into a clean and sustainable energy grid [92].

2.2 Smart City pilots

Looking at the current status towards the realization of the Smart City paradigm, we can observe that it is still far from being realized, due to its highly autonomous and intelligent features. The available technologies are, indeed, not yet sufficiently mature to make Smart Cities truly autonomous. However, there are currently pilot projects worth mentioning.

SmartSantander [96] is a pilot project which has recently received significant attention. This is a unique, in the world city-scale, experimental research facility to support typical applications and services for a Smart City. The testbed deployed has dual purpose; one allows real-world experimentation on IoT related technologies (protocols, applications, etc.), the second is supporting the provision of smart city services aimed at enhancing the quality of life in the city of Santander. Different devices have been installed: *fixed sensor nodes* attached to public lampposts or to building facade, which can observe a wide range of physical magnitudes (e.g., light intensity, noise, carbon monoxide, air temperature, relative humidity, solar radiation, atmospheric pressure, soil temperature, wind direction, etc.); *mobile sensor nodes* installed on top of public transport buses, taxis, and other municipal services vehicles; *parking monitoring sensor nodes* buried under the asphalt on outdoor parking places; *traffic monitoring sensor nodes* buried under the asphalt on the main entrances to the city; *QR and NFC tags* located at city Points of Interest (POI) (e.g., monuments, bus stops, local administration premises, shops, etc.) that represent a key asset for the augmented reality service.

The development of Songdo [103] in South Korea, started from scratch in 2001 and is predicted to be complete by 2018. Smart systems are used in

[1] http://urbancivics.com/soundcity_app.html

every building to monitor the water and electricity, which also allow residents to connect remotely using their smartphones. Sensing technologies include RFID tags on vehicles, which send signals to sensors on the road to monitor traffic flow, surveillance systems as well as smart street lights, which can be adjusted to pedestrian traffic.

Amsterdam has seen some recent developments en route to make it a Smart City. The main operator of this development is Amsterdam Smart City project[2], started in 2009 with the main goal of increasing green growth using technology. Different initiatives started in specific city locations, like for example an intelligent electricity network (Smart Grid) developed in the New West district, which promises to reduce the number and duration of power outages; to improve the opportunity to feed consumer-produced electricity back to the grid; to increase capability to support the integration of electric-powered vehicles, etc.

Other important initiatives involve Barcelona[3]. Sensors have been deployed in garbage bins, allowing remote monitoring of the content of bins and optimizing garbage collection service. Additionally, the City Council installed "smart water" system for tele-managing the irrigation of the city's green spaces, an initiative that is as good for the environment as it is for the economical aspect, with its use of latest-generation technology for better resource management. Sensors on street-lights detect presence and adjust the light intensity accordingly as well.

London and in particular Camden Town, is another active city in the field. Different sensors and data feeds are already available in Camden, like *cameras* used for monitoring traffic, public transport and safe shopping; *GPS and location sensors* used for deriving information about the positioning and the status of waste collection vehicles; *meteorological data feeds* used to provide relevant information to tourists; *traffic data streams* used to balance load on public and private transport; *security data streams* used for monitoring as per national policy directives; *disaster prevention data streams* used for monitoring as per disaster plans and simulations. The aims of Camden is to boost targets of its business strategy like reducing the cost of business operations, with a view to make it an attractive destination of commercial, retail and leisure activities; strengthen Camden's links to neighboring areas/districts (such as Euston and Kings Cross), and so on.

As one of the largest cities in the world, Istanbul has a population of 13.9 million on a surface area of 5313 square kilometers. This cosmopolitan and historic city needs to meet the challenge of maintaining transportation safety and accessibility since it continues to become an important international metropolis with increasing traffic numbers. To ensure effective and efficient use of the current main arterial road network, traffic management

[2]http://amsterdamsmartcity.com
[3]http://smartcity.bcn.cat/en

in Istanbul is a critical issue. To deal with those issues, the idea is to develop, install, maintain and operate Intelligent Transportation Systems and their infrastructure including traffic monitoring and supervision cameras, radar detectors, sensors, and so on.

The project Smart City Písek[4] seeks to introduce modern information technologies into the daily regime of the city. Písek can be considered as the first really intelligent city in the Czech Republic. The use of wireless technology IQRF[5] increases comfort of the city's population via dynamic control of intersections, smart management of public lighting and navigation system on public parking lots. Analysis of all the collected data brings optimization of urban traffic and public transport.

Started in 2012, the Sense-City project[6] will offer a suite of high-quality facilities for the design, prototyping and performance assessment of innovative, micro- and nano-technology based sensors devoted to urban instrumentation. Acknowledging the shortcomings of evaluating sensors performances in laboratory conditions only or in the ever-changing environment of our cities, Sense-City will provide a realistic urban test space in climatic conditions, far more complex than clean rooms and far less complex than actual cities. Sense-City revolves around the mini-city concept, a large, fully customizable climatic hall able to host full- and reduced-scale models of essential urban components. The design of the models will allow for the simulation in climatic conditions of numerous scenarios of sustainable cities. The scenarios to be implemented will correspond to different research topics related to urban sustainability: energy performances in buildings, quality of air, water and soils, quality of fluid distribution networks (gas, sewage, drink water), control of waste disposal areas, durability and safety of infrastructures.

Table 2.1 summarizes the goals of the cities / projects discussed above.

Looking at the aforementioned pilots, it is evident that there is a real need to intervene in the urban environment and make it more livable. The proposed approaches are different; from building a city from scratch -which, of course, is not always possible- to other initiatives that focus on solving a specific problem; therefore they adopt technologies that more suit the use case. In general, the surveyed solutions can be considered as standalone and vertical silos, designed to deal with a particular scenario. The lack of integration among different city actors is evident. It is worth highlighting that some of the above actions have testbed purposes, providing experimental research facility and letting researchers to design and deploy applications and services for Smart Cities.

[4] http://tcpisek.cz/en/smart-city/
[5] http://www.iqrfalliance.org
[6] http://www.sense-city.univ-paris-est.fr

City / Project	Purpose
Santander, Spain	testbed platform; smart parking systems; environmental monitoring; traffic monitoring
Songdo, Korea	smart buildings; tags on vehicles; sensors on the road; smart lighting
Amsterdam, the Netherlands	smart grid; smart energy management
Barcelona, Spain	smart garbage bins; smart-water systems; smart parking; smart lighting
Camden Town, England	traffic data; meteorological data; disaster prevention
Istanbul, Turkey	smart traffic management
Písek, Czech Republic	smart intersections; smart public lighting; parking
Sense-City	testbed around mini-city concept; urban sustainability (quality of air, water, etc.)

TABLE 2.1: Some of the Smart City pilots.

2.3 European Initiatives for Smart Cities

The enormous interest acquired by the Smart City concept is also witnessed from the several initiatives that the European Commission has activated.

The European Innovation Partnership on *Smart Cities and Communities* (EIP-SCC) focuses on the integration of industry, citizen and cities to try to improve the sustainability of the urban life through integrated solutions. The 7th Framework Programme for Research and Technological Development of the European Commission funded different projects under the call Smart City, in order to correctly identify and address Smart City issues and challenges. Without pretending to be exhaustive, we will present some of the most representative projects that have been proposed in the European FP7 calls.

ClouT[7] (2013-2016) uses the Cloud computing as an enabler to bridge the Internet of Things with the *Internet of People* via the *Internet of Services*, to establish an efficient communication and collaboration platform exploiting all possible information sources to make the cities smarter and to help them facing the emerging challenges such as efficient energy management, economic growth and development. ClouT provides infrastructures, services, tools and applications that will be reused by different city stakeholders such as municipalities, citizens, service developers and application integrator, in

[7] http://clout-project.eu

order to create, deploy and manage user-centric applications taking benefit of the latest advances in the IoT and Cloud domains.

SOCIOTAL[8] (2013-2016) aims to design and provide key enablers for a reliable, secure and trusted IoT environment that will enable creation of a socially aware citizen-centric Internet of Things by encouraging people to contribute their IoT devices and information flows. It will provide the techno-social foundations to unlock billions of new IoT information streams taking a citizen-centric IoT approach towards creation of large-scale IoT solutions of interest to the society. By equipping communities with secure and trusted tools that increase user confidence in IoT environment, SOCIOTAL will enable their transition to smart neighborhood, communities and cities.

CityPulse[9] (2013-2016) provides innovative smart city applications by adopting an integrated approach to the Internet of Things and the Internet of People. The project will facilitate the creation and provision of reliable real-time smart city applications by bringing together the two disciplines of knowledge-based computing and reliability testing.

SMARTIE[10] (2013-2016) aims to create a distributed framework to share large volumes of heterogeneous information for the use in Smart City applications, enabling end-to-end security and trust in information delivery for decision-making purposes following data owner's privacy requirements.

Project	**Technology**	
	Cloud	**IoT**
ClouT	✓	✓
SOCIOTAL		✓
CityPulse		✓
SMARTIE		✓

TABLE 2.2: European FP7 projects.

It is important to highlight that all the above European initiatives consider the human and social aspect as crucial; furthermore the use of the Internet of Things is recognized as essential (Table 2.2), defining therefore a common strategy towards the Smart City vision. It is worth underlining that Cloud computing is acknowledged as an enabler of the integration between the IoT and other city stakeholders.

[8] http://sociotal.eu
[9] http://www.ict-citypulse.eu
[10] http://www.smartie-project.eu

2.4 Conclusion

In the last decades, the necessity to improve the quality of life and to make cities sustainable and efficient has lead to success the Smart City paradigm. Anyways, due to its popularity, the concept has been used with different names and in different circumstances, making therefore difficult a formal and universally accepted definition. Recently, a common vision is to describe a Smart City as a complex system that integrates different actors such as people, governance, economy, living, environment, and mobility. In order to achieve this model, a key role is played by ICT and especially by the prominent Internet of Things.

Looking at the current status, we can observe that the realization of the Smart City paradigm is still far from being realized. The real scenario is indeed characterized with a high level of *fragmentation* of technologies and lack of ubiquity in terms of both connectivity and coverage, going therefore against those needs of integration, cooperation, and interoperability required between different Smart City stakeholders highlighted in Chapter 1.

In order to bridge the gap between these different IoT ecosystems, in the next Chapter, the evolution of the Internet of Things -by using Semantic interoperability and Cloud computing- towards the Cloud of Things (CoT) is discussed. Compared to the other -standalone and vertical- solutions, the CoT aims to make better use of distributed resources -by enabling an horizontal integration-, to put them together and making therefore, real the Smart City vision.

Chapter 3

Towards the Cloud of Things

The Internet of Things (IoT) is signing an important revolution in all the aspects of our lives, e.g., work, health, transportation, etc. [107]. Looking at the bigger picture, we can perceive the Smart City concept as a clear example of integration and cooperation among those different IoT ecosystems. Nevertheless, the IoT deployments are, nowadays, based on different standards and protocols, making therefore, difficult and challenging the conception of the Smart City paradigm.

To deal with this problematic, in this Chapter, the evolution of the Internet of Things towards the Cloud of Things (CoT) is presented. Aspects of both visions are analyzed while underlying the need of a technological progression in a Smart City context. Then, the VITAL operating system -which can monitor, visualize, and control all the operations of a city- is shown as a system that embraces the CoT philosophy.

3.1 IoT middleware

Several platforms have been introduced in literature in order to manage IoT devices and deal with specific use-cases. In this field, middleware gained, recently, a lot of importance due to their major role in simplifying the development of new services and the integration of legacy technologies into new ones [6]. In the following, we will present some of the most representative IoT platforms without pretending to be exhaustive:

- *GSN*[1] is a platform developed in Java, aiming at providing flexible middleware to address the challenges of sensor data integration and distributed query processing. It lists all the available sensors in a combo-box which users need to select the ones they need. GSN's purpose is to make the GSN applications hardware-independent and the changes and variations invisible to the application. The main limitation of GSN is due to lack of semantics to model the data and metadata.

[1] https://github.com/lsir/gsn

- *LSM*[2] (Linked Sensor Middleware) is a platform that brings together the live real world sensed-data and the Semantic Web. It provides many functionality such as, wrappers for real time data collection and publishing; a web interface for data annotation and visualization; and a SPARQL endpoint for querying unified Linked Stream Data and Liked Data. However it does not offer tools for manipulating data.

- Fortino et al. in [30] propose a multi-layered agent-based architecture for the development of proactive, cooperating and context-aware smart objects. This architecture takes into account a wide variety of smart objects, from reactive to proactive, from small to very large, from stand-alone to social.

- *Sensor-Cloud* [117] is an infrastructure that aims at managing physical sensors by connecting them to the Cloud. This infrastructure provides the service instances (virtual sensors) to the users in an automatic way at the same fashion as these virtual sensors are effectively part of the IT resources. The generation of the services instances implies that the sensor devices and service templates (used to create the virtual sensors) should be firstly prepared.

- *OpenIoT*[3] represents a joint effort of several contributors to IoT-based applications according to a Cloud computing delivery model. It concentrates on providing a Cloud-based middleware infrastructure in order to deliver on-demand access to IoT services, which could be formulated over multiple platforms.

- *Xively*[4] (formerly Cosm and Pachube) offers a public Cloud that simplifies and accelerates the creation, deployment and management of sensor in scalable way. Its main constraint is due to the limitation to manage and to retrieve data just from own devices.

The aforementioned initiatives strengthen the use of semantic techniques in order to enable the integration of different data-sources. At the same time, also the Cloud computing is recognized as a key player in this integration process. However, a lot of new enhancements are still needed to realize a platform that can offer the means to monitor, control, and visualize all the operations in a city environment.

3.2 Semantic Interoperability

The aforementioned heterogeneous landscape -in terms of hardware capabilities / constraints, network protocols, and application requirements- is

[2] https://code.google.com/archive/p/deri-lsm/
[3] https://github.com/OpenIotOrg/openiot
[4] https://xively.com

in contrast with the Smart City requirements, i.e., *integration* and *cooperation*. In the last years, researchers focused on *interoperability* techniques that allow communication among the disparate devices available.

In [41], authors highlight the need of an IP-based access as unifying network layer that can turn those objects into Internet-Connected Objects (ICOs). At the same time, authors point out on the need of a *semantic representation* in order to understand data which comes out and goes into the ICO interfaces. This *"data exchange layer"* may influence discovery and routing approaches and it will be crucial to enable scalability from an application's point of view, as nobody will be able do deal with the number of ICOs, efficiently and scalable, without such a layer.

The necessary technologies to build this layer are already being developed and deployed: Linked Data [11] and the Resource Description Format (RDF) [43] are accepted standards in the Web and provide a general model. Our approach is therefore, to use those solutions that are already widely accepted.

3.2.1 Linked Data

The term Linked Data is usually applied to a set of techniques for publishing and interlinking structured data on the Web. As stated in [44], Linked Data is based on four principles:

1. Use URIs as names for things. Each thing has a globally unique name, usually an HTTP URI since this makes easy to enforce global uniqueness.

2. Use HTTP URIs. It makes easier to retrieve description of things using HTTP protocol. For humans the description can be provided as HTML page and for machines it can be provided as RDF triples.

3. Use standards to provide information. This usually means that standards like RDF are used to model and access data.

4. Use link to other URIs. This operation enables the possibility to discover more things. That means that there should be external links pointing to other data sources on the Web. By following these links, a larger and distributed data space can be explored automatically.

To summarize, Linked Data enables the implementation of generic applications operating over a huge, interconnected and distributed data space by using Web standards and a common data model.

The most common data model used in the context of Linked Data is the Resource Description Framework (RDF).

3.2.2 RDF and JSON-LD

RDF is a popular standard for describing things (known as resources or entities). It is a graph-based data model that represents information as labeled directed graphs. Each triple *(s, p, o)* consists of a subject *s*, a predicate *p*, and an object *o*. The predicate denotes the relationship between subject and object.

The example in Figure 3.1 shows a representation in RDF; the information "The sea has the color blue" is modeled as a triple with "Sea" as the subject, "has color" as the predicate, and "blue" as the object. Both the subject and the predicate are identified by URI while the object can be a URI or a literal value (i.e., a string or a number).

FIGURE 3.1: RDF example.

RDF provides just a data model; to format data, a number of different technologies exist, i.e., RDF/XML, Turtle, N-Triples, and JSON-LD. Anyway, many developers have little or no experience with formats such as N-Triples and Turtle, therefore the use of JSON-LD is preferred.

JSON-LD is, indeed, a JSON-based serialization for Linked Data. Its main features are:

- **Simplicity**. No need for extra processors or software libraries.
- **Compatibility**. JSON-LD documents are always valid JSON documents, so standard libraries from JSON can be used.
- **Expressiveness**. Real-world data models can be expressed because the syntax serializes a directed graph.
- **Terseness**. The syntax is readable for humans and developers need little effort to use it.
- **Zero Edits**. JSON-LD can be devolved easily from JSON-based systems, in most of the cases.
- **Usable as RDF**. JSON-LD can be mapped to/from RDF and can be used as RDF without having any knowledge of RDF.

Listing 3.1 shows a description of a person (Bob Dylan) based on JSON-LD data format. The *context* links object properties in a JSON document to concepts in an ontology. By having all data semantically annotated as in the example, an RDF processor can identify that the document contains information about a person (*@type*) and if the processor understands the FOAF vocabulary it can determine which properties specify the person's name and homepage.

LISTING 3.1: JSON-LD example.

```
{
  "@context": {
    "name": "http://xmlns.com/foaf/0.1/name",
    "homepage": {
      "@id": "http://xmlns.com/foaf/0.1/workplaceHomepage",
      "@type": "@id"
    },
    "Person": "http://xmlns.com/foaf/0.1/Person"
  },
  "@id": "http://bobdylan.com",
  "@type": "Person",
  "name": "Bob Dylan",
  "homepage": "http://www.bobdylan.com"
}
```

3.2.3 Ontologies

Linked Data can be used in cases in which data is originated from different sources. To integrate all data, therefore, it is important to have some rules in order to determine how the RDF graph has to be built and how triples may be connected or not. These rules are given by ontologies.

An ontology specifies formally the conceptualization of a domain of interest. To define ontologies, the W3C published the Web Ontology Language[5] (OWL) which builds on RDF.

Many ontologies have already been developed, and among them, the Semantic Sensor Network (SSN) [18] answers the need for a domain-independent and end-to-end model for sensing applications. Within the SSN context, a sensor could be anything that observes; be it an electronic object, a virtual object or a human. Figure 3.2 shows the ten modules and key concepts and relations of the SSN ontology. The full ontology consists of 41 concepts and 39 object properties: that is, 117 concepts and 142 object properties in total, including those from DUL (DOLCE+DnS Ultralite)[6].

To better understand the ontology in terms of sensors and observations, the four main perspectives of SSN ontology are explained below:

- *Sensor perspective*. A sensor is described with a stimulus, a sensing method, observation, and capabilities. One sensor may have many measurement capabilities. Such capabilities are e.g., measurement precision, measurement range, accuracy, and measurement resolution.

- *Observation perspective*. It describes an observation. An observation includes a context for interpreting incoming stimuli and puts the observation event into an interpreting context.

[5] http://www.w3.org/2001/sw/wiki/OWL
[6] https://www.w3.org/2005/Incubator/ssn/wiki/DUL_ssn

- *System perspective*. A system can have sub-systems or sub-concepts like devices and sensing devices.
- *Feature and property perspective*. It focuses on properties -sensors that sense some distinct property- or on observations -made about a distinct property-.

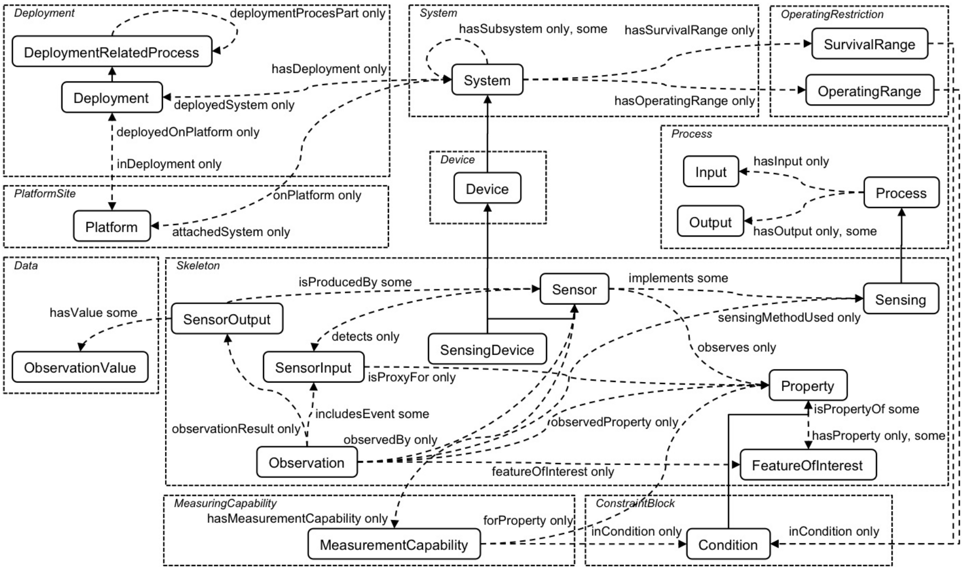

FIGURE 3.2: The SSN ontology - concepts and relations.

Semantic techniques are recognized as good enablers in the complex process of integration of heterogeneous data-sources. As seen, those technologies are already available and adopted in some of the most popular middleware solutions. However, once modeled and homogenized, there is still the need to physically store those data-sources and easily access them while ensuring scalability; in the next Section the Cloud computing is introduced as in order to face these challenges.

3.3 The Cloud computing

In the last decades, *Cloud computing* attracted the attention from both academia and industry across the world, thanks to its capability to transform in service model the entirely current IT (Information Technology) industry.

The main advantages introduced by Cloud computing are high performance, high availability, infinity scalability, tremendous fault-tolerance capability; at the same time, it minimizes the upfront investment [117].

According to Patidar et al. [73], the Cloud services can be divided into three main categories. As resumed in Table 3.1, they are:

- *Infrastructure as a Service* (IaaS) offers computing resources such as processing or storage (e.g., Amazon Web Services (AWS), Cisco Metapod, Microsoft Azure).

TABLE 3.1: Cloud Computing - main service models.

Service Model	Objective
IaaS	Extend current data center infrastructure for temporary workloads
PaaS	Increase developer productivity and utilization rates while decreasing an application's time-to-market
SaaS	Replace traditional on-device software

- *Platform as a Service* (PaaS) is designed for software developers; it allows them to write their applications without needing to worry about the underlying hardware infrastructure (e.g., Apprenda, Google App Engine, Apache Stratos).
- *Software as a Service* (SaaS) is the most visible layer of Cloud Computing for end-users; it concerns the actual applications that are accessed and used (e.g., Google Apps, Citrix GoToMeeting, Cisco WebEx).

In addition to the aforementioned layers, many others have been presented and discussed in literature; i.e., Data as a Service (DaaS), Network as a Service (NaaS), up to the Everything a a Service (XaaS) model reported by Banerjee et al. in [8]. It promotes the **"pay as you go"** method, which allows the consumption of a service by paying only for the amount of resources used.

This approach is at the base of the *Sensing as a Service* (SeaS) model introduced by Perera et al in [77]. Authors characterize four main layers:

- *Sensor and Sensor Owners layer* is used by sensors' owners in order to manage sensors and to allow, or not, their publication into the Cloud.
- *Sensor Publishers layer* detects the available sensors, communicates with the owners, and gets permission to publish them.
- *Extended Service Provider layer* communicates with multiple Sensor Publishers in order to select sensor based on customers' requirements.
- *Sensor Data Consumers layer* is the layer that manages the final consumers of sensors data.

The benefits and advantages expected by the SeaS are attractive and numerous; to name a few: *sharing and reusing sensor data* -no need to deploy other sensors, consumers can access the ones already available by paying a fee-, *reduction of data acquisition costs* thanks to the shared nature, *collect data previously unavailable* -due to the business model, companies will be stimulated to "sell" sensors data-.

Within the Smart City context, these features can play a crucial role. Indeed, this model can be applied to *things* that are already deployed and that sense the urban environment. Therefore, it will be possible to exploit all the capabilities/services offered by those devices, without the need to install new ones.

3.4 The Cloud of Things: VITAL-OS

The Semantic interoperability together with the Cloud computing is at the basis of the Cloud of Things (CoT) paradigm. The CoT aims to make a better use of distributed resources, to put them together in order to achieve higher throughput and to be able to tackle large scale computation problems.

The Cloud of Things enables, therefore, the horizontal integration of various (vertical) IoT platforms and applications, making feasible the realization of the Smart City vision. Moreover, it allows users to express the services they want; providing them relevant data without asking to manually select the sensors which are relevant to their requirements.

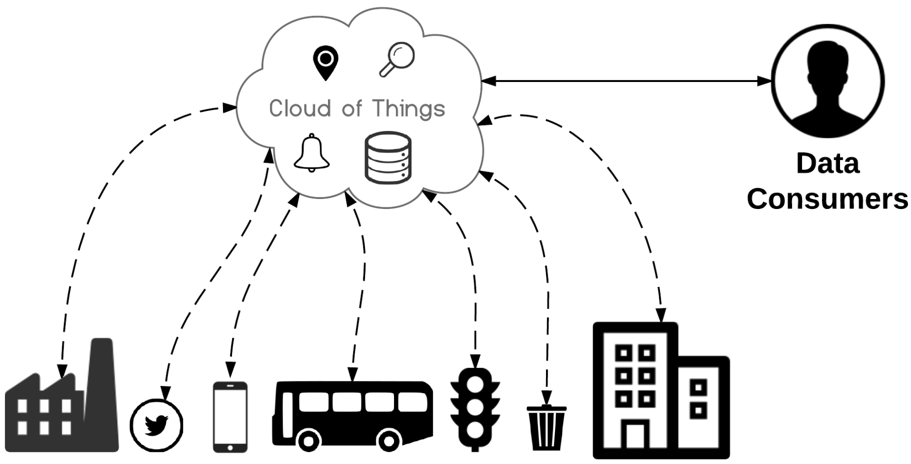

FIGURE 3.3: Cloud of Things.

As shown in Figure 3.3, the Cloud of Things is a catalog in which different heterogeneous data-sources -i.e., sensors deployed in buildings, roads, lamppost, cars, semaphores, etc.- are stored and formatted according to semantic reasoning. Those resources can be easily searched and accessed, via a common interface, by data consumers in order to retrieve important information. For example, let us suppose that a user aims to create an application for monitoring the speed in a street; without the need to deploy new sensors, he/she can search in the CoT for devices that have the required sensing capabilities (e.g., speed sensor) and that are already available in the street at hand. At this point he/she can chose the one that better suits his/her use case.

VITAL[7] is an European Commission funded project, which embraces the Cloud of Things philosophy. One of the most important objectives of VITAL is, indeed, the integration of Internet-Connected Objects (ICOs) among multiple IoT platforms and ecosystems. A very key factor, in this context, is represented by the virtualization of interfaces in combination with cross-context tools that enable the access and management of heterogeneous objects supported by different platforms and managed by different administrative stakeholders. This layer allows the development, deployment, and operation of IoT applications for Smart Cities, thereby turning VITAL into an operating system that can monitor, visualize, and control all the operations of a city [97].

In order to integrate in a platform-agnostic way a multitude of heterogeneous data and functionalities, produced by disparate (independent) organizations and entities, the VITAL-OS leverages on Semantic interoperability and Cloud computing functionality.

In order to model and access data, VITAL combines different ontologies (Table 3.2). To describe sensors, including accuracy, capabilities, observations, methods for sensing, and survival ranges, VITAL leverages on SSN. Beyond this, other basic concepts like time, location and unit of measurement are modeled via well-known ontologies such as *OWL Time ontology* [46], and *Quantities, Units, Dimensions and Data Types Ontologies* [47]. To deal with Smart City scenarios, it is also important to define and model concepts for the following headings:

- *transport*, e.g., dynamic route calculation informing about accidents and congestion;
- *energy*, e.g., reporting of faults;
- *emergency services*, e.g., detection of accident and crimes;
- *recreation*, e.g., producing data on large events such as concerts to inform public transport about possible congestion.

The majority of the VITAL semantic information on cities are obtained via the classic DBpedia dataset[8]. However, modeling Smart Transport is a non-trivial task since it covers a wide range of domains (e.g. tracking pedestrian congestion, smart traffic light systems, etc.). Therefore, VITAL uses, again, a combination of ontologies, and the core of them is the Ontology for Transportation Networks (OTN) that allows an easy modeling of a transport network graph with connections between infrastructures (e.g., bus) as well as dynamic events such as accidents and blocked passages.

It is important to emphasize that, a user who would like to adopt VITAL for other Smart City aspects, can do so by specifying additional ontology

[7] http://www.vital-iot.eu
[8] http://dbpedia.org

TABLE 3.2: VITAL ontologies.

Prefix	Ontology - Language	Namespace
dcn	Delivery Context ontology	http://www.w3.org/2007uwa/context/deliveryContext.owl#
dul	DOLCE+DnS Ultralite ontology	http://www.ontologydesignpatterns.org/ont/dul/DUL.owl#
geo	Basic Geo (WGS84) ontology	http://www.w3.org/2003/01/geo/wgs84_pos#
hrest	hRESTS ontology	http://www.wsmo.org/ns/hrests#
msm	Minimal Service Model ontology	
owl	Web Ontology Language	http://www.w3.org/2002/07/owl#
rdfs	RDF Schema ontology	http://www.w3.org/2000/01/rdf-schema#
sawsdl	Semantic Annotations for WSDL and XML Schema ontology	http://www.w3.org/ns/sawsdl#
ssn	Semantic Sensor Network ontology	http://purl.oclc.org/NET/ssnx/ssn#
time	OWL Time ontology	http://www.w3.org/2006/time#
vital	VITAL ontology	http://vital-iot.com/ontology#
wsl	WSMO-Lite ontology	http://www.wsmo.org/ns/wsmo-lite#
xsd	XML Schema Definition	http://www.w3.org/2001/XMLSchema#
qudt	Quantities, Units, Dimensions and Data Types Ontologies	http://qudt.org/schema/qudt#
foaf	Friend of a Friend	http://xmlns.com/foaf/
s4ac	Social Semantic SPARQL Security for Access Control	http://ns.inria.fr/s4ac/v2#
otn	Ontology of Transportation Networks	http://www.pms.ifi.lmu.de/rewerse-wga1/otn/OTN.owl

elements in an easy and documented way. Thanks to the nature of Linked Data indeed, additional elements can be added at any time without the need to redesign the whole system.

3.4.1 The VITAL-OS architecture

As shown in Figure 3.4, the VITAL architecture is organized in three main layers, which in turn are composed by different modules.

1. **IoT Platforms and Data Sources**. It is the lowest layer of the architecture, where various IoT systems -i.e., platforms, applications, and data sources- reside. This layer is therefore, composed by various IoT systems that are virtualized and integrated as parts of the architecture. In order to validate the architectural concept, data from several IoT platforms -i.e., x-GSN, Xively, Hi Reply, and FiT IoT/lab- is integrated and processed. Additional platforms and/or applications can

be integrated as soon as these expose a well defined Platform Provider Interface (PPI).

This layer is composed by a sub-layer named *Platforms Access and Data Acquisition* (PADA). Its role is to access the low-level capabilities of the IoT Systems (through PPI) and to transform the acquired data and metadata into a common data model (i.e., VITAL ontology).

2. **Platform Agnostic Management, Monitoring and Governance**. This layer provides Cloud-based functionality for managing data and metadata that comply with the VITAL ontology. The platform agnostic data management layer offers a wide range of services to higher level applications, which reside in the added-value functionality layer. These services are accessible in a virtualized platform and location agnostic manner, through VUAIs (Virtualized Unified Access Interfaces). VUAIs are abstract interfaces, residing at the top layer of the architecture, that allow the implementation of a kind of abstraction where "objects" handler -which points to physical items- can be discovered, selected, and filtered.

   - *Data Management Services (DMS)*. It provides Cloud-based functionality for managing data and meta-data. The offered services include data and meta-data persistence, creation of new data, and more. The DMS communicates, via REST interfaces, directly with PADA, Added Value Services and the VUAIs (Virtualized Unified Access Interfaces).
   - *ICO & Services Discovery (SD)*. This module provides the means for discovering ICOs in the scope of horizontal integrated IoT applications spanning multiple platforms and business contexts. It directly interacts with the DMS in order to discover the "appropriate" resources for a particular business context.
   - *Filtering*. It provides the means for reducing the information associated with individual data streams persisted in the platform agnostic data management layer. Therefore, it reduces unwanted information, thereby optimizing processing performance and economizing on network bandwidth.
   - *Complex Event Processing (CEP)*. It enables the processing of datastreams for multiple sources in order to identify patterns and/or infer events.
   - *Orchestration*. Its role is to combine and manage multiple services from the above-listed modules, in order to deliver new added-value services. The combination of the various services is based on a workflow of service oriented components and interactions, which may be specified on the basis of rules.

3. **Smart City Applications and Tools**. At this layer, the VITAL-OS supports the integration, deployment, and operation of Smart City applications, leveraging data from multiple IoT platforms and applications and offering several easy-to-handle tools that allow users to design their own application for Smart City.

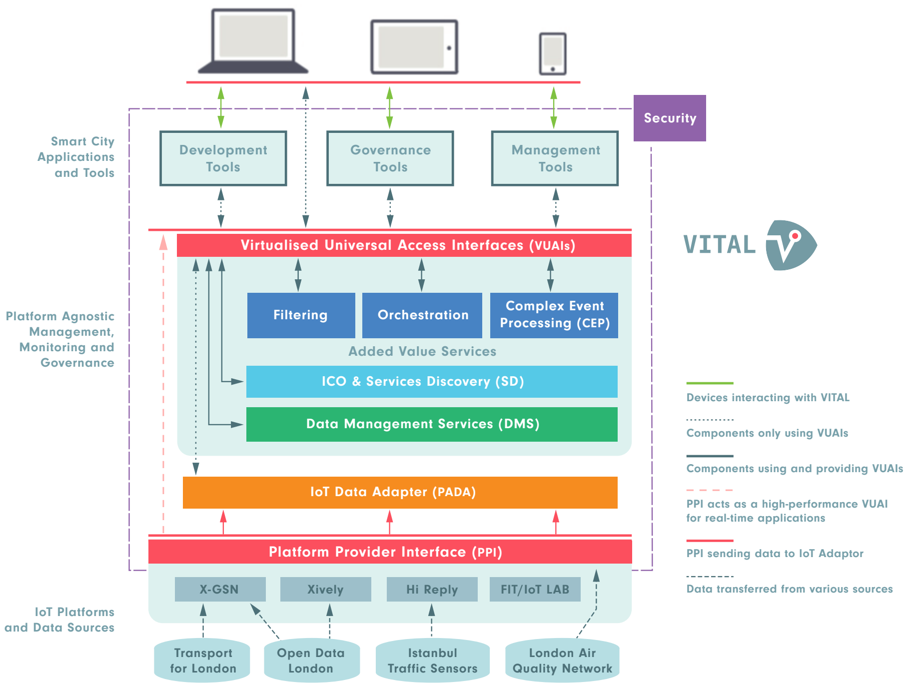

FIGURE 3.4: VITAL-OS architecture.

As seen, VITAL is designed and implemented in order to virtualize, integrate, develop, and deploy IoT applications for Smart Cities, notably applications that leverage data and services from multiple IoT systems. The development of the VITAL architecture is driven by the different principles and characteristics:

- *Maximum reuse*: the VITAL architecture is specified in a way that maximizes reuse of available IoT platforms and components
- *Virtualization*: the VITAL platform boosts a virtualization approach to accessing and processing data from multiple IoT platforms and applications.
- *Standards-based*: the VITAL architecture is specified and implemented taking into account popular standards for data modeling, data exchange (e.g., XML, RDF) and system integration technologies (e.g., SOA, RESTful technologies).
- *Driven by VITAL scenarios*: the specification of the VITAL architecture is striving to satisfy the reference scenarios.

3.4.2 VITAL-OS use cases

Smart Traffic Management. In the last years, the technological advancements have allowed a very deep diffusion of complex GPS navigators. Several drivers make use and exploit these tools, that give very valuable information on the traffic conditions also in real time. They are also very valuable in the case of accidents alerts. Anyway, also in this context, the VITAL platform, through the definition and implementation of its Cloud of Thing paradigm, is able to play a key role. Let us refer to a scenario where an accident is broadcast/"alerted" (e.g. through the use of a GPS navigator). Normally, after such an alert occurs, the "minor" roads are taken as viable alternative solutions, with the side effect that they will be soon overcrowded. Moreover, this type of navigators does not take special events into consideration, such as concerts or festivals. The elaboration of data coming from different ICOs allows a smarter elaboration of different kinds of information. In this regard, the VITAL platform does not limit its "intervention" to a simple alert and alternative roads, but the VITAL services will output alternatives that consider many different "aspects" and the final user will play an active and aware role by choosing based on different types of information.

Smart Street Management. An effective management of the roads would make easier the citizens' life and would also have an economic impact. Just as an example, we could consider Public Lightening Management, which represents a significant source of energy wasting. In this context, the VITAL platform "reinterprets" every light source (each equipped with sensors) as an Internet-Connected Object (ICO). The VITAL services (e.g. Discovery, Filtering, and CEP) allow an efficient management of the information, through the interconnection of data originated from different Clouds. This intelligent manipulation of the data will be exploited in several ways such as: 1) it will be translated in "actuation" for an automatic regulation of the luminous intensity; 2) it will be used to infer useful information such as the actual schedule of public transportation (e.g. whether a bus is incoming and the exact number of the bus); 3) it will be used for the intelligent management of the trash containers (e.g. if a trash container has to be emptied), etc. In practice, the concept of services as defined in the VITAL platform is to allow the manipulation and management of data coming also from zones that are geographically far to each other also through the definition and implementation of complex algorithms.

3.5 Conclusion

In this Chapter, the evolution of the Internet of Things towards the Cloud of Things -by using Semantic interoperability and Cloud computing- has been illustrated. The CoT is a paradigm that enables the horizontal integration of various (vertical) IoT platforms and applications, making therefore, feasible the realization of the the Smart City vision. In order to validate this vision, the VITAL operating system -which embraces the CoT philosophy- has been examined.

In this context, the discovery of appropriate data-sources that satisfy user requirements, represents one of the most important challenges. In the next Chapter, the discovery of data-sources will be argued.

Chapter 4

Discovery of resources

One of the most important challenges within the Smart City context, is the discovery of appropriate data-sources that satisfy user requirements. More than 50 billion of devices are attended to be connected to the Internet by 2020 [26], then, it is crucial to have mechanisms capable to provide, in an efficient way, resources that better suit business criteria defined by users. The community refers to this challenge as service discovery [76].

The discovery is an operation that can be performed directly *in-network* (i.e., the detection of neighbors) and/or *out-network* (i.e., a middleware that aims to discover resources that belong to different networks). In this Chapter, both processes are discussed by introducing two different solutions: the VITAL ICOs & Services Discovery, which offers *out-network* functionality and CACHACA, a ranking mechanism for Sensor Networks that deals with *in-network* tasks.

4.1 Out-network discovery: VITAL ICOs & Services Discovery

In the *out-network* discovery, the challenge concerns the representation of different data-sources and how users can easily access those resources and the provided services. Generally, those IoT services, are published into registers that are available as end-points of IoT platforms.

Within the VITAL-OS, the Discoverer module -horizontally integrated in the platform itself as shown in Chapter 3- is responsible for discovering ICOs, Systems, and Services. Although the discovery of Systems and Services represents an important business for the whole architecture, in this Section, we only focus on the ICOs.

The VITAL ICOs & Services Discovery (SD) offers its functionality to other modules, via a RESTful web service [28]; queries are embedded in the body of an HTTP request and represented using JavaScript Object Notation (JSON) Standard.

The discovery process is performed on data stored in the DMS; this operation is achieved without regard to the underlying platform handling

TABLE 4.1: VITAL ICOs & Services Discovery - ICOs request parameters.

NAME	TYPE	DESCRIPTION
type	String	Category assigned to ICO
position	Object	Keys to perform discovery over spatial region
latitude	Number	Latitude's value expressed in WGS84 standard
longitude	Number	Longitude's value expressed in WGS84 standard
radius	Number	Distance in Kilometers from the center or the Area of Interest
observes	String	Measuring properties provided by an ICO
movementPattern	String	Select ICO registered with a specific movement pattern
connectionStability	String	Select a specific level of connection stability
hasLocalizer	Boolean	Select ICO with localizer services (i.e., GPS)
timeWindow	Number	Time in minutes; represents the time window for position estimation

the ICOs. This represents, therefore, a key feature as the platform agnostic property is one of the goals proposed by the architecture. Internet-Connected Objects being part of VITAL, are described by a set of metadata that characterizes the nature of an element. Thanks to this information, ICOs can be classified according to their properties. Such a classification is essential for the later discovery of all the elements stored in the system and that suit the criteria defined by users. The main properties that can drive a discovery process are:

- **Position**. It represents the last known position of an ICO -expressed in latitude and longitude coordinates-. Such values can be immutable in the case of a *stationary node* or it can change over time for a *mobile node*.
- **Mobility**. It describes the mobility type of an Internet-Connected Object. Every node can be configured as being *Stationary*, *Mobile*, or *Predicted* -in this latter case the mobility pattern is known-.
- **Connectivity**. It provides information about the capability of a node to be connected over the Internet and a description of the connection stability.

- **Observation capability**. It describes all the properties that a node can observe (e.g. Speed, Footfall).

All the above parameters are modelled according to the VITAL ontology [45]; a detailed list of those properties is available in Table 4.1.

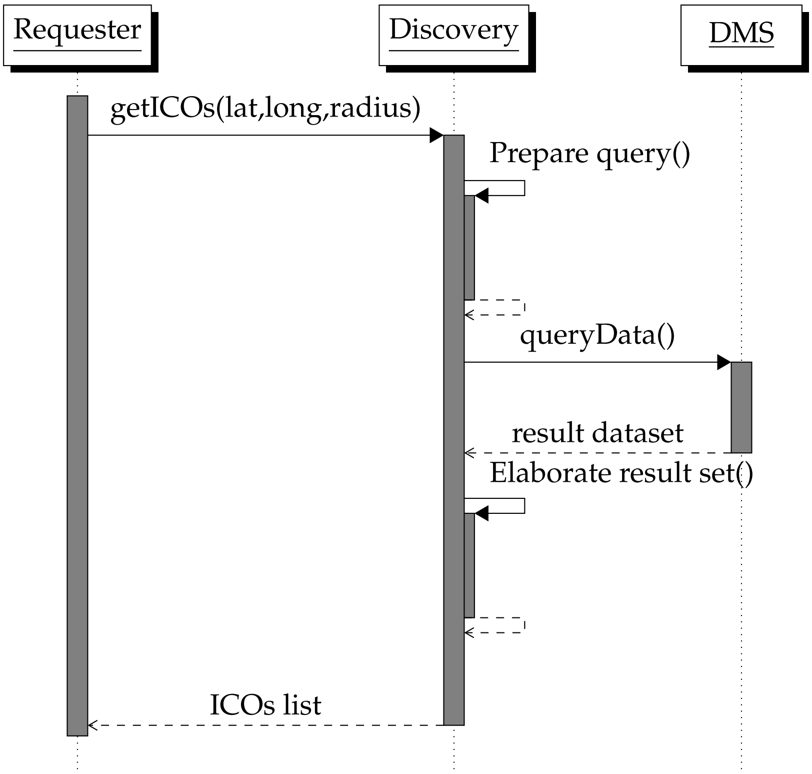

FIGURE 4.1: VITAL ICOs & Services Discovery - example of interactions.

Figure 4.1 shows how the SD interacts with other modules in order to execute an assigned task.

Upon reception of a request, the DISCOVERY re-formulates the query. In order to perform a geographical search, it is necessary to compute latitude and longitude boundaries. Given a center position (*lat - long*) and a distance (*radius*) in kilometers, the conversion process aims to compute minimum and maximum values for both latitude and longitude. This computation is performed using the law of haversine [42] defined in spherical trigonometry, which relates sides and angles of spherical triangles. Once the query is ready and modelled according to the VITAL ontology, it is sent to the DMS, which will respond with a data-set of available ICOs matching the request parameters. At this point, the SD applies its rules -giving priority to ICOs that are closer to the Point of Interest, have good connection, etc.- in order to provide back to the REQUESTER an organized list of ICOs.

In order to have a time estimation about the above operations, we deployed the SD module on WildFly[1] -an application server written in Java, which implements JAVA EE specifications- and we performed experimentation with parameters available in Table 4.2.

[1] http://wildfly.org

TABLE 4.2: VITAL ICOs & Services Discovery - experimentation parameters.

Parameter	*Value*
Application server	WildFly 9.0
Processor	Intel Core i5 (2.6 GHz)
RAM	8 GB
DMS Deployment	Galway, Ireland
Number of ICOs	> 10.000
Number of Systems	> 100
Number of Services	> 10

Figure 4.2 sums up the main results; we can observe that the SD takes, in average, less than 2 seconds in order to discover a generic ICO, System, or Service registered in the VITAL's DMS. To avoid time out issues, we implemented a timer of 5 seconds, after which the SD returns with an error to the REQUESTER. Regarding the CPU, each query is performed in 32 milliseconds.

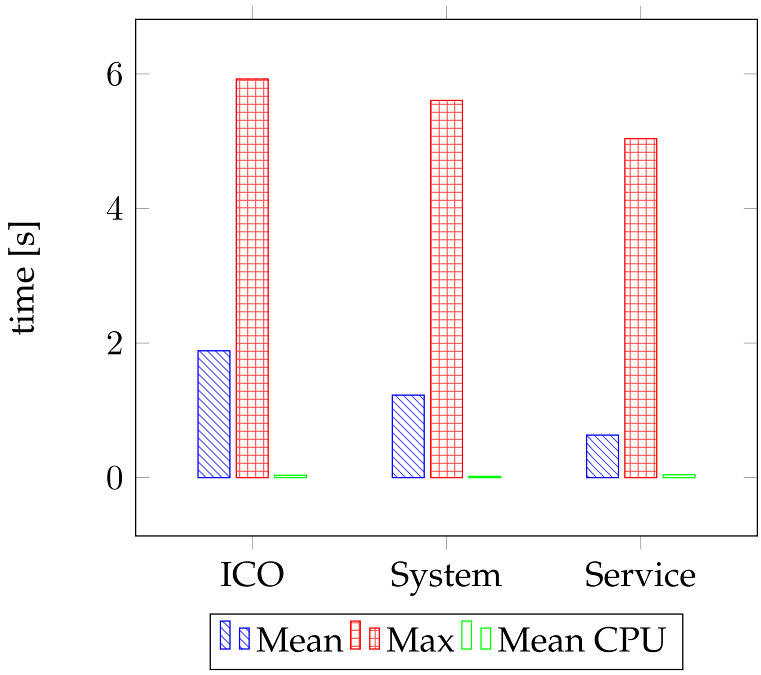

FIGURE 4.2: VITAL ICOs & Services Discovery - performance.

4.2 In-network discovery: CACHACA

The *in-network* discovery process is more related with the building and maintenance of the network itself, especially in order to introduce new services and devices.

A variety of protocols exists and is used nowadays for TCP/IP networks [10]; to name the most well known, Service Location Protocol (SLP), developed by IETF and Universal Plug and Play (UPnP) developed by Microsoft. A lot of effort has also been done for resource-constraint networks; in [100], Shelby et al. present COAP; in this case, services are published into a register -which can be queried by users- stored at the gateway.

As stated in Chapter 3, introducing a "data exchange layer" could influence discovery and routing approaches and it can be crucial to enable scalability. The benefits of semantic annotation are widely explained in [25]; to summarize, the most representative are: *(i)* re-use of Machine-to-Machine (M-2-M) data by many applications; *(ii)* "write-once run-anywhere" applications; *(iii)* easy adaptation in case of failures/changes of the available sensor sets.

In order to constitute semantic information in our context, two main options arise: either to use standardized data types, like the one defined by the IPSO Alliance in [99], or rely on ontologies, like the SSN ontology. Niu et al. [69] proposed a context-aware service ranking approach by aggregating the user rating and WSN service context but do not consider a single device but rather the whole network. Durmus et al. [23] propose a discovery protocol based on semantic representation of services; the mechanism operates in the network layer and can directly run SPARQL queries on top of those devices. Anyway, this approach is not suitable for SN context due to the lack of resources. Finally, in [110] authors introduce a ranking strategy by estimating the cost of accessing sensor services using properties of the sensor nodes as well as relevant contextual information extracted from the service access process.

In order to overcome the limitations of a centralized solution and evaluate the services quality, we proposed a ranking mechanism for Sensor Networks that facilitates the discovery of services.

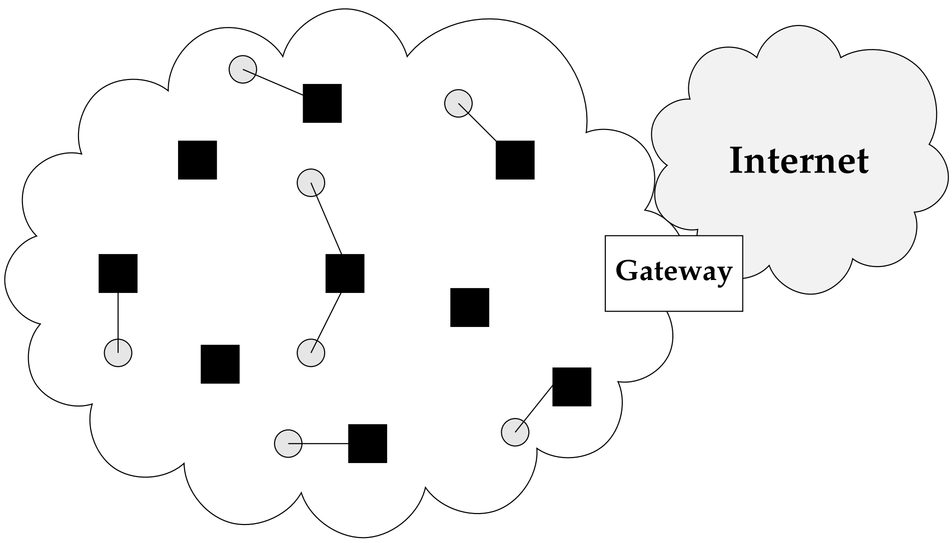

FIGURE 4.3: CACHACA - network elements: *node* (square), *sensor* (circle).

4.2.1 Assumptions and metrics

CACHACA distinguishes three different network elements (see Figure 4.3):

- *1)* a ***node*** (square) that has communication capabilities, and therefore able to communicate with other elements. If a node is equipped with some sensors (circles) we refer to it as **full node**; then it is capable to measure physical events, for example providing the temperature of a room, or the availability of a parking spot;
- *2)* a ***relay*** is a node with communication capabilities;
- *3)* a ***gateway*** that is a node in charge of gathering and managing data produced by sensors, and at the same time, enhanced to act as an end-point for the communication with the Internet or with other local devices. In this work we consider a gateway just as a service provider, like a node.

We assume that a Neighbor Discovery mechanism -prerequisite for the network construction and routing [113, 109, 16]- is running on each node u to allow u the discovery of other nodes v in communication range. So, at a frequency f, each node receives information about its neighborhood that it stores in a Neighbor Table (NT). Note that the exact format of NT is implementation-specific, but according to [108] it should contain, at least, the following for each neighbor v of u:

- *numTx*: number of transmitted packets to v;
- *numTxAck*: number of packets acknowledged by v;
- *numRx*: number of packets received from v;
- *Timestamp* of the last frame received from v;
- *Connectivity statistics* (e.g., RSSI, LQI), which can be used to determine the quality of the link.

At the same time, we suppose that each node uses a standardized format (e.g., IPSO [99]) for describing its services (i.e., temperature, light, humidity, etc.). Each service is combined with other complementary information such as:

- *freshness* of the information; can be real-time or temporized;
- *provider*: to specify whether the service is directly provided by the node itself or by a neighbor.

The above parameters can be used in order to define relationship of a node with the neighborhood, and therefore to select the ones that are more reliable in function, for example, of their connectivity statics or mobility patterns. In this sense, in this work we use some of the above parameters in order to introduce two additional functions, the PHYSICAL CONFIDENCE (φ) -based on the *RSSI* and *Timestamp*- and the SERVICE CONFIDENCE (ω) that is computed based on the service information.

RSSI represents the measured power of a received radio signal; it is widely used in different standards (e.g., IEEE 802.11). According to [106], the RSSI is reported as an integer ranging from $-100\ dBm$ to $0\ dBm$; in this work we normalize it as a value from 0 to 100.

4.2.2 Fuzzy logic

In order to compute the physical confidence, we use a rule-based fuzzy inference system [118]. A fuzzy logic system can be developed in three steps:

1. **Definition of fuzzy sets (fuzzification).** In this first round non-fuzzy inputs (i.e., numbers) are converted into fuzzy sets by using membership functions (e.g., triangular, trapezoid, singleton, bell, or some other type of function).

2. **Definition of fuzzy rules.** Expressed as statements like "IF ... THEN ...", the fuzzy rules summarize the relationship between the fuzzy sets and the output variable.

3. **Defuzzification.** This last stage is used to convert the fuzzy output back into a value that can be later used to make decisions.

4.2.3 Physical confidence computation

The physical confidence is computed based on fuzzy logic rules applied to RSSI and timestamp collected by the neighbor discovery protocol in a local and distributed way by each node u for each of its neighbors v. We thus consider three fuzzy sets based on the RSSI values : BAD, GOOD, and EXCELLENT. Figure 4.4 shows the diagrammatic representation of the RSSI that is computed using a trapezoidal membership function.

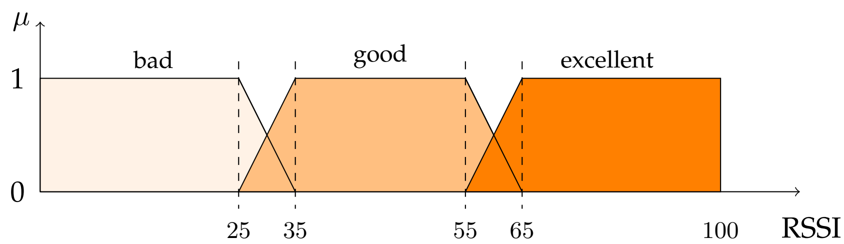

FIGURE 4.4: CACHACA - diagrammatic representation of RSSI.

The other parameter used for the estimation of φ is the Timestamp; in this case, we consider the difference Δt (Eq. 4.1) between the instant at which the computation process is executed (t_{now}) and the Timestamp $t_{timestamp}$ stored into the NT.

$$\Delta t = t_{now} - t_{timestamp} \tag{4.1}$$

Once Δt is obtained, we consider again three fuzzy sets: BAD, GOOD, and EXCELLENT. Since we supposed that the application is time-constrained, we favor small values of Δt (Figure 4.5); therefore a node that provides services in real-time will be highly preferred to one with higher values of Δt.

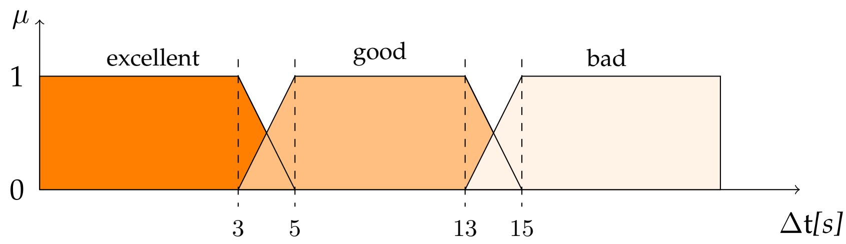

FIGURE 4.5: CACHACA - diagrammatic representation of Δt.

After completing the fuzzification process, we apply the fuzzy rules to obtain the physical confidence. Table 4.3 shows the definition of the rules in CACHACA. An example can be observed as: "**IF** RSSI is *Excellent* **AND** Δt is *Excellent* **THEN** φ is *Excellent*". It is worth noting that we give more importance to the time parameter. Indeed, when the RSSI is *Good* and Δt is *Excellent*, neighbors are still noted as *Excellent*; this is because a communication can be completed even with lower RSSI, on the other end, if the neighbor is not often active, it is important to classify it as *Bad*.

TABLE 4.3: CACHACA - rule based fuzzy inference.

$RSSI$	Δt	φ
Excellent	Excellent	Excellent
Good	Excellent	Excellent
Excellent	Good	Good
Good	Good	Good
Bad	Excellent	Good
Excellent	Bad	Bad
Good	Bad	Bad
Bad	Good	Bad
Bad	Bad	Bad

4.2.4 Service confidence computation

The service confidence (ω) is computed by each node considering one of its mono-modal services per time (e.g., temperature); in this case we use just the *Freshness* feature. As shown in Table 4.4, ω is considered *Excellent* when it is possible to access in real-time to the values of the services.

TABLE 4.4: CACHACA - service confidence computation for a Full node.

Provider	*Freshness*	ω
sensor	real-time	Excellent
sensor	temporized	Bad

Yet, a node is now able to characterize the different confidence values for each of its neighbors periodically, for each packet received. Algorithm 1 describes how the physical confidence is updated by u upon reception of a new packet from v. u checks whether v is already stored into its NT, if so, it updates its NT with the *RSSI* and the *Timestamp* and then it computes φ for each node present in its NT. If not, a new entry will be added, with the ID of v, the *RSSI* and the *Timestamp*; at this point u computes φ for each neighbor by applying the fuzzy logic rules above presented.

Algorithm 1 Physical confidence update - Run on node u upon reception of packet from node v.

```
if v ∈ NT then
    update RSSI and Timestamp values for v in NT;
else
    add v in NT with associated RSSI and Timestamp;
end if
∀ w in NT, update φ(w) following Table 4.3.
```

In order to discover efficiently the different services available, nodes advertise their services and the associated confidence periodically and can relay the information about a service offered by a neighbor. The format of the frame is shown in Figure 4.6; the *Service* uses 10 bytes, while the confidence can be transmitted by using only 1 byte. Considering that the length of the MAC frame of IEEE 802.15.4 can be maximum 127 bytes, and subtracting 31 bytes of header and 2 bytes of footer, in one message we could advertize up to 8 services.

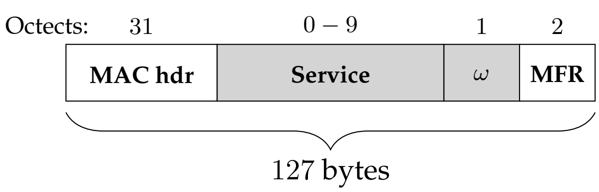

FIGURE 4.6: CACHACA - frame format with *Service* and *Service confidence*.

Upon reception of such a message from a neighbor v, a node u can thus upgrade entry of v in its NT with these values as shown in Table 4.5; for each neighbor, the information stored will be: the offered *Service*, the *ID*, the two *confidences* (physical and service), the *RSSI*, and the *Timestamp*. This Neighbor Table is used to evaluate the neighborhood and to rank the neighbors. Furthermore, the NT can be cleaned by removing deprecated entries for space saving purposes.

TABLE 4.5: CACHACA - Neighbor Table.

ID	$Service$	ω	φ	$RSSI$	$Timestamp$
1	temp	excellent	good	80	1431108000
30	light	good	good	50	1431108008
2	temp	excellent	excellent	90	1431108007
...					

When the information about a service is relayed, the ω confidence is also function of the physical confidence. Table 4.6 shows how ω transmitted by the relay node is influenced by φ and ω of the Neighbor that provides the service; the best value that we can obtain is *Good* and it is verified when the $\omega_{Neighbor}$ is *Excellent* and $\varphi_{Neighbor}$ is *Excellent* or, at at least, *Good*; while, even when the $\omega_{Neighbor}$ is *Excellent*, ω will be *Bad* if the $\varphi_{Neighbor}$ is *Bad*. Algorithm 2 and Figure 4.7 show the process of advertisement of a service by a relay node; this can be done only when the ω is *Good*.

TABLE 4.6: CACHACA - service confidence computation for a Relay node.

$\varphi_{Neighbor}$	$\omega_{Neighbor}$	ω
Excellent	Excellent	Good
Good	Excellent	Good
Good	Bad	Bad
Bad	Bad	Bad
Bad	Excellent	Bad

Algorithm 2 Service confidence computation for a Node. - Run at node u upon reception of a packet from v

if $v \in$ NT **then**
    update NT(*RSSI, Timestamp*) for NT.*ID*;
else
    store v in NT with associated RSSI and Timestamp;
end if
$\forall w \in$ NT **do** update $\varphi(w)$ with Table 4.3
if (($\varphi(w)$) = (*Excellent*)) || (($\varphi(w)$) = (*Good*)) **then**
    compute $\omega(w)$;
    if (ω = (*Good*)) **then**
        broadcast (Service, ω);
    end if
end if

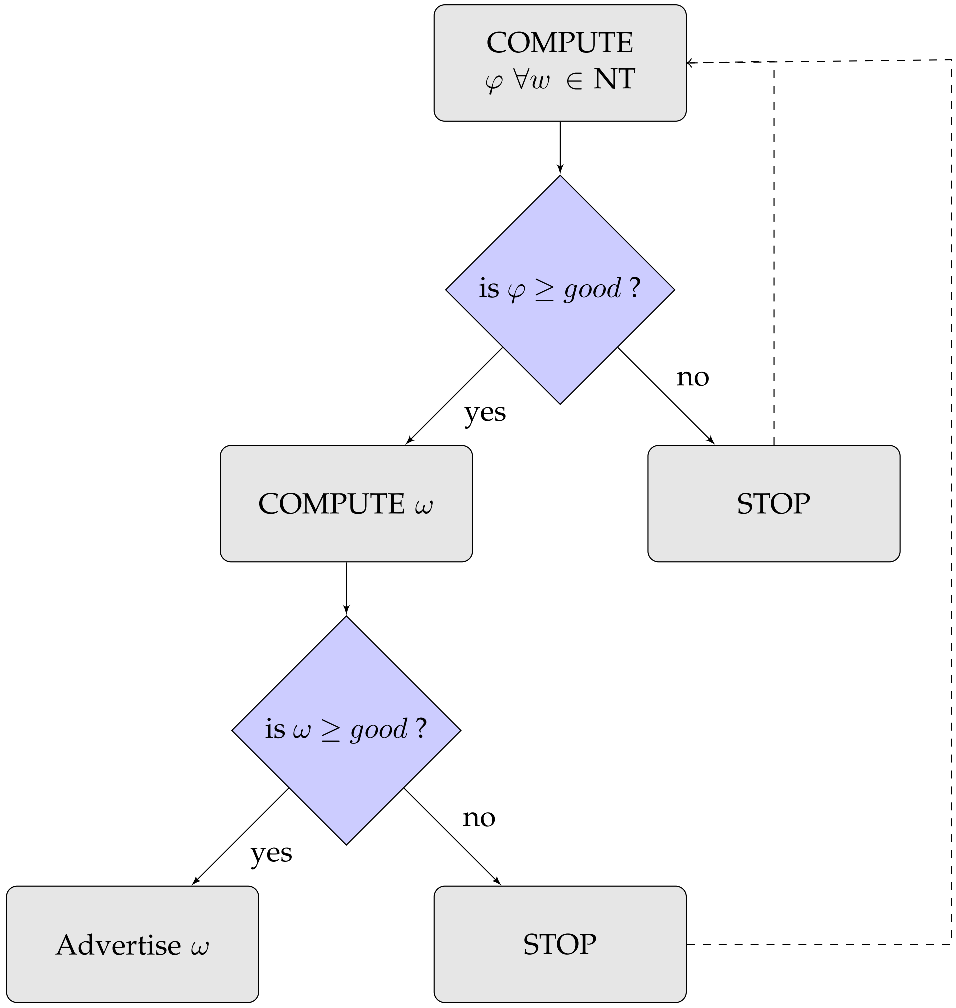

FIGURE 4.7: CACHACA - Stages.

4.2.5 Performance Evaluation

To evaluate the performance of CACHACA, we use Contiki-OS[2] and its simulation tool Cooja; Table 4.7 summarizes the principal parameters. Among the others (e.g., TinyOS[3], Riot[4]) we choose Contiki because its good assessment by the community, its completeness and re-usability; with Contiki indeed, it is possible to run simulations and then re-use the code to flash real devices. We consider an area of 160 m^2, in which M network elements are randomly positioned; M is the sum of R relays equipped with 1 sensor. Values of M and R and what they stand for, depend on the scenario under evaluation as detailed later.

We use the following metrics to assess the performances of CACHACA:

- $service_{avg}$ represents the average number of services discovered by each node;

[2] http://www.contiki-os.org
[3] http://tinyos.net
[4] http://www.riot-os.org

TABLE 4.7: CACHACA - simulator parameters.

$Parameter$	$Value$
Nodes radio chip	CC 2420
Nodes flash memory	1 MB
Simulation seed	random
Simulation runs $\forall$ scenario	30 [75]

- $neighbor_{avg}$ is the average number of neighbors discovered by each node;
- $packets_{avg}$ is the average number of packets transmitted by each node;
- ω_{avg} is the average value of the service confidence ω computed by each node;
- φ_{avg} is the average value of the physical confidence φ computed by each node.

We performed the simulations in five different scenarios (Table 4.8). In all scenarios, the Number of Services is set to 10; it means that we will have 10 nodes that periodically advertise their own services. In the first Scenario, we have just the 10 nodes running, while in the second and third scenarios we introduce some relay nodes. In the last two Scenarios, we consider that relay nodes can move inside the area with an average speed of 1 m/s (preferred human walking speed).

TABLE 4.8: CACHACA - simulator scenarios.

	$Services$	R_{fix}	R_{mobile}	M
Scenario1	10	0	0	0
Scenario2	10	2	0	25
Scenario3	10	50	0	50
Scenario4	10	0	25	25
Scenario5	10	0	50	50

This set of Scenarios can be used to describe a generic smart city use case (e.g., smart building). A number of different sensors is available in distinct rooms; those sensors can offer services like temperature, luminosity, and so on; other devices (attached for instance to the smart-phones of employed) act as relay for the sensors' services. We chose to use only 10 Full nodes and evaluate the number of relays necessary to discover all the potential services. Moreover, we vary the number of relays between 0 and 50 because we want to study the behavior when the network is dense and therefore evaluate how CACHACA discovers reliable services. A number of nodes equals to 50 is considered enough [24] for some Smart City applications such as pollution monitoring, alerting, etc. Simulation results are reported with the 95 % confidence intervals.

4.2.6 Simulation results

Figure 4.8 shows the average number of packets sent per node. We can observe that the $Packet_{avg}$ increases at the beginning; while this number decreases when there are more relays on the network. This is because relay nodes advertise a service offered by a neighbor only if this service has $\omega =$ *Excellent* and the φ of the neighbor is at least *Good*.

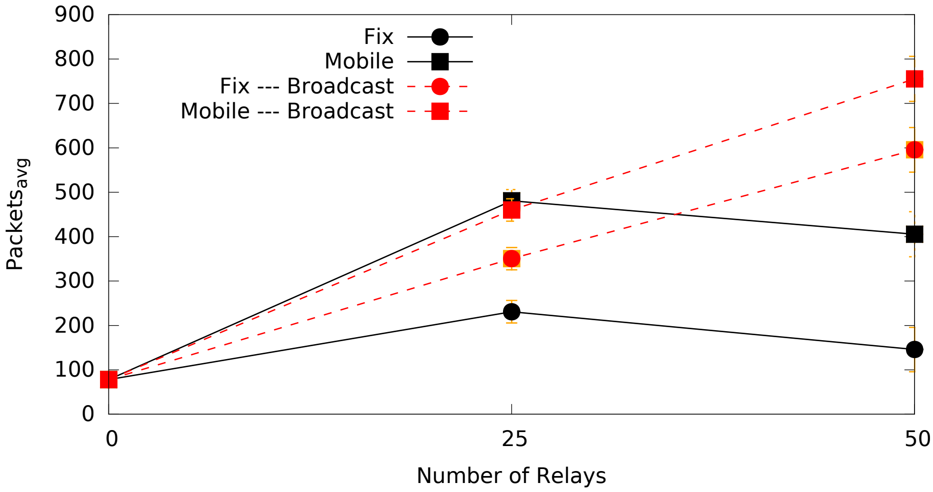

FIGURE 4.8: CACHACA - Number of Relays vs. Packets$_{avg}$ sent.

Introducing mobility makes $Packets_{avg}$ increase because of the higher possibility to meet nodes and therefore for relay to advertise services. For the sake of equity and fairness, we have also considered that relay nodes broadcast a service immediately when it is discovered, without taking account of the quality (dashed lines in the Figure). In this case, we can observe that the number of messages increases intensely and so also the quality of the channel and the energy consumption will be negatively affected.

Figure 4.9 indicates the average number of Neighbors and Services discovered by each network element (in 10 minutes) in function of the Number of Relays. In the first Scenario, the 80% of the nodes are discovered, therefore also the associated services will be discovered. When we increase the number of relays, we can observe that performance regarding the discovered neighbors discrease, while all the services will be discovered. With mobility, the performance regarding the neighbors improve; each node is capable to discover about 100% of the available reliable services and more than 75% of neighbors. These results show that when the number of relays in the network is higher the service discovery process is more efficient.

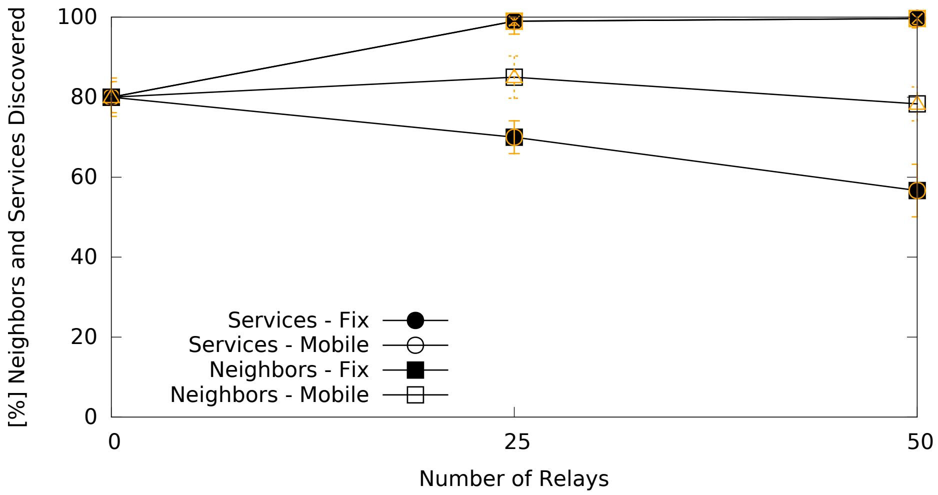

FIGURE 4.9: CACHACA - Number of Relays vs. Services and Neighbors Discovered.

In the last investigation (Figure 4.10), we consider the behavior of φ and ω in function of the Number of Relays. We can observe that in the first Scenario both the physical and the services confidences are close to *Excellent*. Then, when the number of relays increases, the performace decrease; this is due to possible interference on the channel. However, we can highlith that -even in the last Scenario- each node can discover all the services provided with a confidence higher than *Good*. When we consider the mobility scenarios, the performance are worst. Anyway, it is important to highlight that even when φ is *Bad*, a communication can happen.

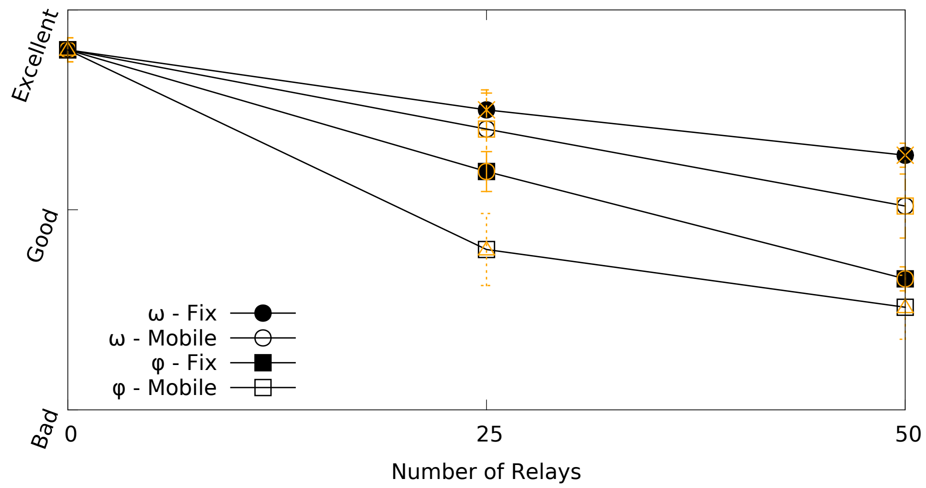

FIGURE 4.10: CACHACA - Number of Relays vs. Physical and Service Confidence.

4.2.7 Experimentation results

In order to face CACHACA to a realistic environment, we ran experimentation on FIT (Future Internet of Things) IoT-lab[5]; a very large scale infrastructure facility suitable for testing small wireless sensor devices and heterogeneous communicating objects over large scale. We used the Rennes site, and we performed experimentation (parameters available in Table 4.9) using Scenarios $1, 2$ and 3 (no mobility).

TABLE 4.9: CACHACA - experimentation parameters.

Parameter	*Value*
Nodes type	WSN 430
Nodes radio chip	TI CC 2420 @ 2.4 GHz
Nodes flash memory	1 MB

Figure 4.11 shows the reliable Services and the Neighbors discovered. We can observe that when there are no relays, each network element discovers about the 80% of the available Services and neighbors; performance regarding the discovery of reliable services are better whe we increse the number of relays. Those results are in line with the ones obtained running simulation with Cooja; therefore we can conclude that when we increase the Number of Relays the efficiency of our proposal -in terms of services discovered- is higher.

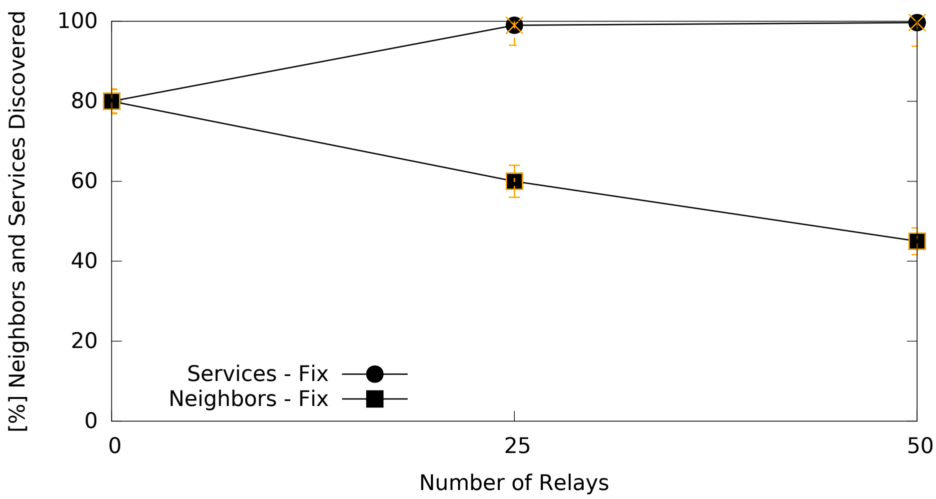

FIGURE 4.11: CACHACA - Number of Relays vs. Service and Neighbor Discovered (FIT IoT-lab).

[5] https://www.iot-lab.info

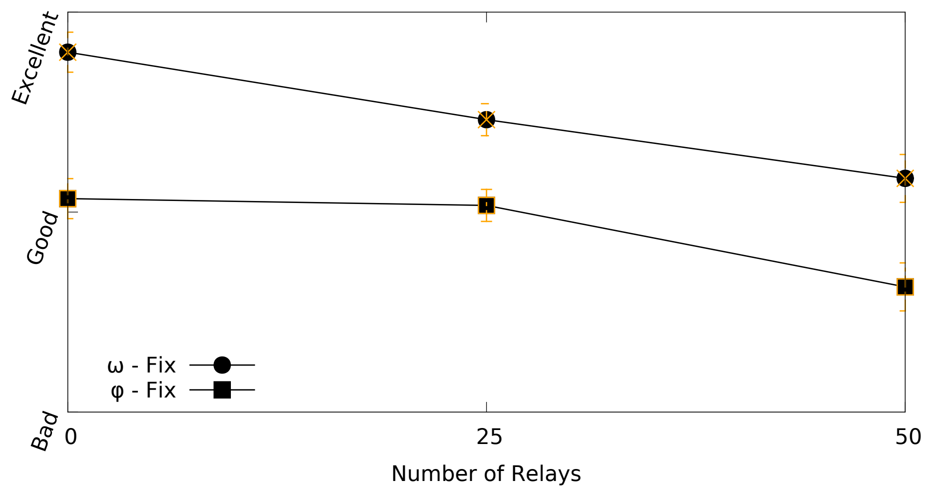

FIGURE 4.12: CACHACA - Number of Relays vs. Physical and Service Confidence (FIT IoT-lab).

Regarding the Physical and Service confidences (Figure 4.12), we can observe that both parameters have better performance when the network is sparse; this is because, the services are directly provided by the direct neighbor, without the intervention of relay; φ decreases with the Number of Relays, because of more interference. The trend obtained in this analysis is once again complementary to the one obtained with the simulator.

4.3 Conclusion

In this Chapter, two complementary mechanisms to discover resources have been presented. The discovery of appropriate data-sources represents, indeed, an important task, especially in context where a huge number of resources is available (i.e., a Smart City).

The VITAL ICOs & Services Discovery aims to address the *out-network* problematic by taking account of different parameters in order to evaluate and better organize ICOs that best suit the business context defined by users. Future enhancements to this module can be introduced by considering machine learning techniques [114] to predict the position of ICOs, and considering other properties (e.g., battery consumption) to drive the discovery process.

Regarding the *in-network*, the proposed CACHACA aims to discover and to evaluate the services provided by each network element. One important aspect that should be analyzed regards the use of other metrics for the evaluation and ranking of the neighborhood and the offered services. Indeed, regarding the Physical Confidence, we used the RSSI as parameter, but this metric sometimes does not represent a good index due to the complex propagation environment. However, CACHACA has been designed to be highly customized, therefore it will be easy to adopt other metrics (e.g., packet delivery ratio). Another important aspect that should be better analyzed is the mobility. Nevertheless, we introduced some results in a mobile scenario, it could be interesting to apply mobility models [104] and to implement and test CACHACA on real mobile hardware.

To make possible the communications and interactions among different sensing devices (running CACHACA for example), and the Internet, in the next Chapter, the design of a gateway for the Cloud of Things is presented. The gateway is able to manage semantic-like things and at the same time to act as end-point for the presentation of data to users. Moreover, thanks to the use of virtualized software, the gateway enables a lightweight and dense deployment of services.

Chapter 5

A gateway for the Cloud of Things

In the past few years similar concepts to Cloud of Things, such as Capillary Networks [95] and Fog Networks [12], consider in their topology the presence of intelligent nodes that -even with limited computation resources- can easily manage the assigned applications. Those nodes are designed to bring bandwidth-intensive content and latency-sensitive applications closer to the data-source [13].

Following this approach, named Edge Computing, in this Chapter, the design of a gateway for the Cloud of Things is proposed. The gateway is able to manage semantic-like things and to act as an end-point for the dynamic presentation of real world data to consumer applications and users. Moreover, thanks to the use of the emerging virtualization technologies, the gateway enables a lightweight and dense deployment of services.

5.1 Towards distributed Cloud

Current literature presents several proposals of network architecture in which the convergence between Cloud and Internet of Things represents the key factor to enable large-scale IoT systems. Many of those solutions require the presence of a gateway capable to provide specific functionalities between the backbone network -Cloud or in general the Internet- and the Sensor Network.

Chen et al.,in [15], list a set of requirements and common features that an IoT gateway must include. In particular, it has to act as a proxy that interconnects the sensor domain with the backbone network. The outlined features are: (i) *multiple interfaces*, needed to avoid possible mismatch between the technology employed by the sensors to connect with the IoT gateway and the rest of the network with the IoT gateway itself; (ii) *protocol conversion* in order to address the issues aforementioned; (iii) *manageability* that refers to the need, for the gateway, to be managed by external servers and to control, configure and operate with sensors.

In [35], Gubbi et al. present a Cloud-centric vision for IoT networks; the authors consider an Internet-centric environment, in which all the services are in support of data produced by the sensors. In the proposed architecture, the presence of several Internet gateways is expected. The function of such devices is exclusively to provide communication between the sink node and the "outside world" through the Internet. Another function performed by the gateway is to enable an efficient addressing scheme. Indeed, one important issue that can be faced in IoT networks is due to the different addressing scheme used by the sensors to respect other network entities. To address this problem, the association of a Uniform Resource Name (URN) to a gateway is proposed.

The design of the gateway proposed in [34] is characterized by the use of the Host Identify Protocol (HIP) that allows global addressing of all the objects connected in the sensing domain, while maintaining the use of IPv4 addresses. The mechanism is structured in such a way to allocate a single public IP-address to a large group of sensors devices, which are in turn under control of a single HIT gateway. In order to facilitate the interactions between different HIT gateways and other functionalities, orchestration mechanisms are proposed by the authors.

In [20], authors introduce an IoT architecture in which a device called "Wireless Gateway" provides functionality of backbone between M-2-M (Machine-to-Machine) devices and remote peers (i.e., client) over the Internet. Even in this case, the gateway is designed to erase the existing heterogeneity between sensing domain and network. More in detail, the wireless gateway is characterized by two different interfaces; the first one provides discovery functionality to mobile clients, and enables clients to detect M-2-M devices and to retrieve data from them. The second interface -which is a collection of REST web services- delivers management and storage functionality just for the M-2-M devices.

The paper [21] presents a Cloud Computing based platform for a specific use case: the management of mobile and wearable healthcare sensors. In this particular scenario, the role of the gateway is to collect all the inputs coming from the sensors and to forward them to the Internet. The authors make use of a mobile phone to perform all the gateway operations. Moreover, the gateway uses a set of REST web services to transmit the sensed data to the Cloud. Similar solutions can be found in [33] and in [19].

Merlino et al. in [63], propose a Cloud-oriented environment in order to integrate IoT paradigms and resource ecosystems in a Smart City scenario; authors use OpenStack[1] as Cloud solution infrastructure.

In [36], authors propose a smart IoT gateway that has three important benefits; it can communicate with different networks, it has flexible protocol to translate different sensor data into a uniform format, and it has unified external interfaces.

[1] https://www.openstack.org

Gyrard et al. in [37], introduce a method to integrate a semantic engine in IoT contexts by taking into account standardization efforts in M-2-M environments. Semantic rules are integrated in the main actors who characterize the network architecture such as cloud, end-point devices, and M-2-M gateways.

Fog computing is another network paradigm, which aims to extend the traditional Cloud computing operations to the underlying network, with a special direction for IoT networks. In [12], authors present a set of guidelines to enable Fog computing networks. The main objective is provide several services such as computation, storage, and networking on IoT nodes. Contrarily to the Cloud paradigm, which is usually strictly centralized, Fog computing provides all the services in a distributed way.

Following this trend, the European Telecommunications Standards Institute (ETSI) has introduced a new network architecture model named as Mobile Edge Computing. According to [72], Mobile Edge Computing enables Cloud computing capabilities at the edge of the cellular network and close to the end-point device itself. Similarly to the concepts aforementioned, the idea behind this new paradigm is that moving part of the processing tasks closer to the device can bring several benefits by enhancing the performance with ultra-low latency and high bandwidth.

To summarize, although the presence of a gateway as an interface between sensor domains and backbone networks is provided in several of the analyzed architectures, its functionalities are often limited to traffic forwarding and protocol conversion. The architecture proposed in this work, includes further features that take advantage of the lightweight and versatile container-based virtualization and the use of semantic techniques to enable an horizontal unification of different data-sources.

5.2 Lightweight virtualization technologies

In the context of the Cloud of Things, data-centers can play an important role regarding offline analysis of large amount of data. To accomplish real-time operations -specially on small time-scale- different actions are required. From this point of view, a distributed Cloud can meet all the requirements of such scenarios, and address numerous issues. In the distributed Cloud [62], the services are not only able to be run in a data-center, but also close to the device itself, for example in the IoT gateways. The amount of data produced by sensor networks can reach several gigabytes; often, this data is affected by a discrete level of redundancy, which has to be reduced by means of operations like filtering, compressing, and other processing operations. Additionally, based on data analysis, there might need to perform actions on the devices. As stated in [62], those operations *"should be done as close to the data-source as possible, preferably already on the* *capillary gateway before data is sent over the uplink. Each application requires its own way of performing compression, filtering and aggregation."*

Furthermore, a bad network performance can become the bottleneck for the whole system. For example, particular IoT services, such as high-bandwidth sensors (e.g., cameras), might have very strict latency requirements. A centralized Cloud would make these IoT services much more dependent on latency and delay issues without ensuring optimal performances. On the other hand, moving part of the computation closer to the sensors and enabling ubiquitous computation, would bring several benefits. In most of the cases, all the operations described before have to be instantiated only temporarily, within a short period of time, and in an efficient way.

The entities that characterize a distributed Cloud topology (Figure 5.1) may have different requirements based on hardware capabilities. For example, a gateway is less powerful than a server in terms of processing power. Therefore, emerging lightweight virtualization technologies -such as containers- can introduce several benefits, which match with the following requisites: *fast initialization, low overhead, and good energy efficiency*.

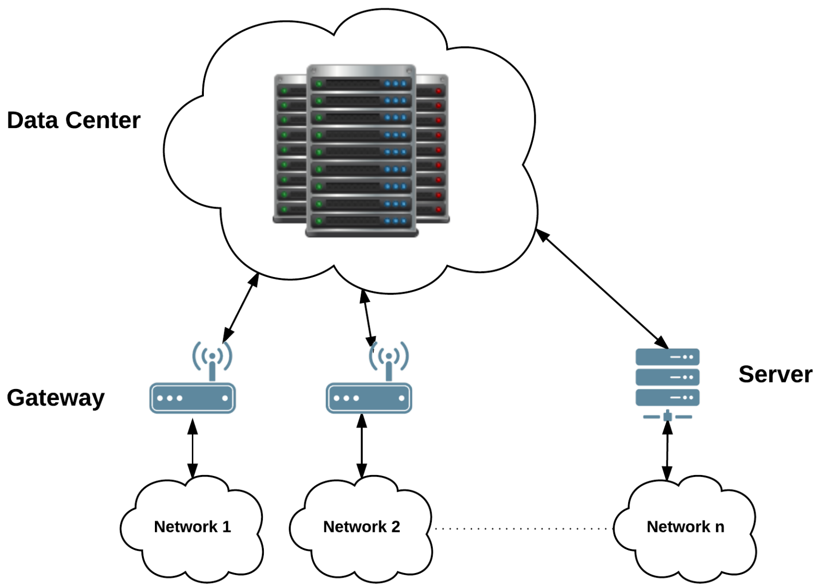

FIGURE 5.1: Distributed Cloud topology.

Traditional hypervisor-based virtual machines may not be the most appropriate means to provide processes virtualization in low-power consumption devices. Indeed, hypervisor-based virtualization operates at hardware level by installing a full operating on a virtual machine. This emulation increments the use of system resources. On the other hand, container-based virtualization can be considered a lightweight alternative to hypervisor-based virtualization. Containers implement, indeed, isolation of processes at the operating system level, avoiding then the overhead due to virtualized hardware and virtual device drivers. The overhead is therefore smaller compared to the one introduced by other virtualization alternatives [66].

Multiple containers can run even in resource constrained devices such as the one used within the IoT landscape. Despite they share the same operating system, each running container operates with independent characteristics: independent virtual network interfaces, independent process spaces, and a separate file system. An example of container-based virtualization architecture is showed in Figure 5.2.

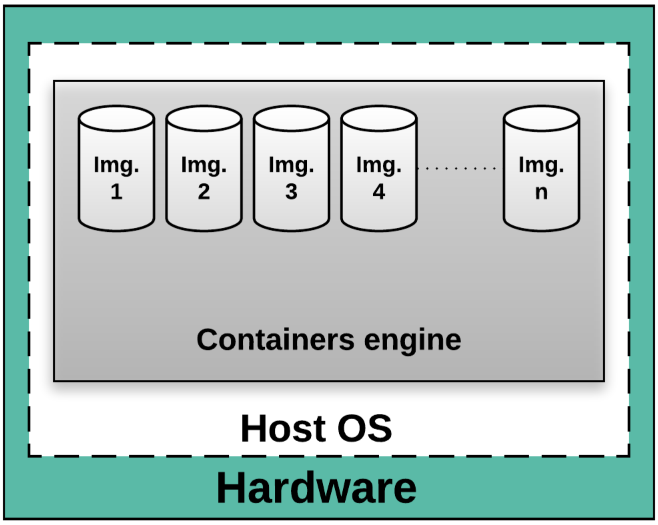

FIGURE 5.2: Container-based virtualization architecture.

The concept of "containerization" is not new in virtualization, but it has gained much more relevance and practical use recently with the advent of Docker[2]. In a Docker container, one or more processes/applications can run simultaneously. Moreover, an application can be designed to work in multiple containers, and to interact with others. This approach is therefore useful in the Internet of Things context; thanks to the Docker containerization indeed, different applications -i.e., database, interface to the Internet, interface to the sensor network, etc.- are available on the gateway and activated only if required optimizing performances in terms of used resources and energy consumption.

The Docker architecture is characterized by three main components:

- *Docker images* are defined as a read-only templates. These templates represent the basic entity from which Docker containers are created.

- *Docker registries* are public or private repositories where Docker images are stored. From this registries, it is possible to upload or download images.

[2] https://www.docker.com/

- *Docker containers* are the running components of Docker. Containers are created from Docker images.

5.3 Design of the gateway

The gateway proposed in this Chapter, leverages on the use of container-based architecture, in order to virtualize different processes and interfaces. As shown in Figure 5.3, the gateway can gather and manage data produced from different sensor networks, and at the same time, it is enhanced to act as end-point for the communication with the Internet.

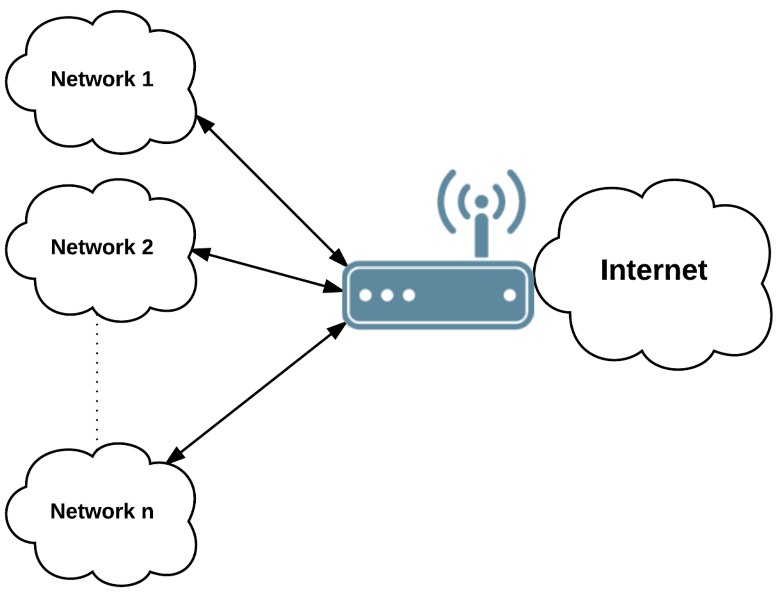

FIGURE 5.3: Gateway for the CoT - network topology.

The interactions of the gateway with sensors and/or other entities are multiple and may occur depending on a particular use case. Along with the traditional routing and forwarding functionality, the proposed gateway is able to support further applications. Within the IoT scenarios, services may be instantiated only temporarily and in an efficient way, for example because of the strict latency requirements of some application. Therefore, introducing containers in such an environment allows a system that benefits from all the features explained in the previous Sections -fast instantiation and initialization and high density of applications/services due to the small container images size-.

The dynamic allocation of applications -by means of containers- brings, indeed, several benefits from the energy and the customization perspective. All the container instances running on the gateway (e.g. databases, etc.) can be dynamically allocated when required, without being constantly active.

Many are the scenarios in which the gateway can interact with the external world. As shown in Figure 5.4, the gateway can be designed to support the communication with different Sensor Networks that use different radio technologies (i.e., IEEE 802.15.4, Wi-Fi, Bluetooth, etc.). In this case, for each technology/protocol, a Docker image should be available at the gateway.

Moreover, the gateway can be enhanced to enable Semantic processing and reasoning between those different data-sources. In order to present sensed data to consumer applications and users, different interfaces can be available in different Docker image.

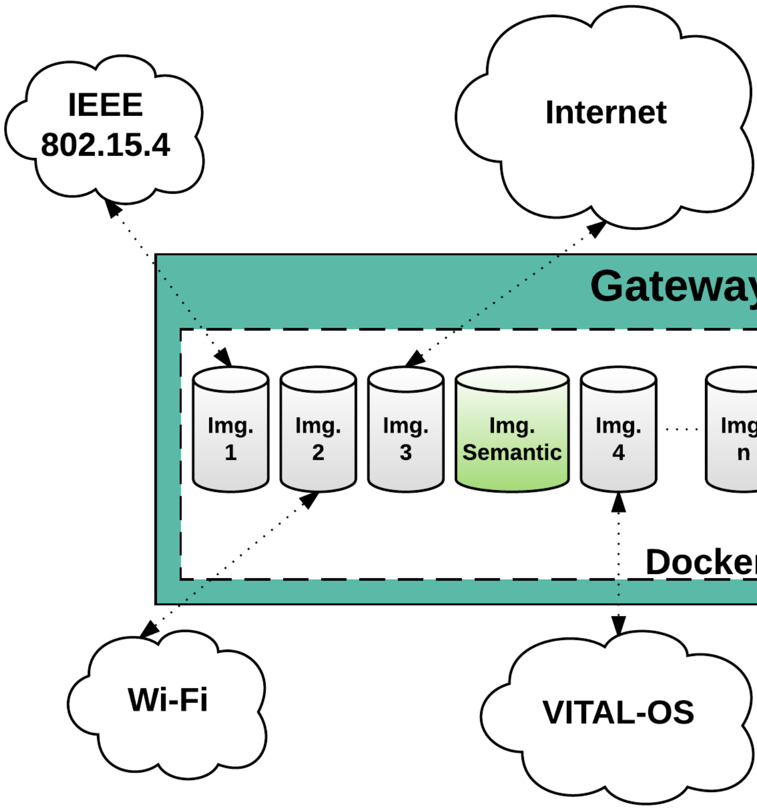

FIGURE 5.4: Gateway for the CoT - interactions.

5.3.1 Performance

To validate the proposal, we run it on real hardware and performed experimentation validation. We used a Raspberry Pi 2[3] as gateway (Figure 5.5); it is equipped with a quad-core ARM Cortex-A7 CPU, with 1 GB of RAM. Furthermore, it has 4 USB ports, 1 Ethernet port, and 40 GPIO pins. One important reason that led to use a Raspberry Pi 2, is the possibility to run containers on top of it[4].

The Raspberry Pi 2 has been tested -in terms of performance- to specific workloads generated by applications running within Docker containers.

[3] https://www.raspberrypi.org/products/raspberry-pi-2-model-b/
[4] http://resin.io/blog/docker-on-raspberry-pi/

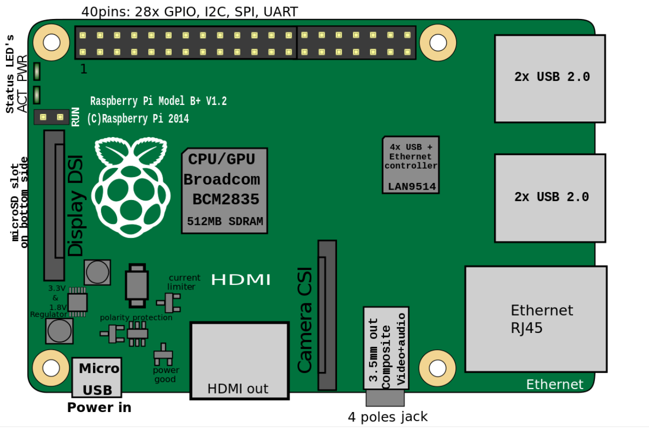

FIGURE 5.5: Raspberry Pi 2 - Model B. (source http://wikimedia.org)

Benchmark tools are used to generate different types of workloads capable to challenge a specific hardware segment. In order to estimate the overhead produced by the presence of a virtualization layer, *CPU*, *Memory*, and *Disk I/O* are tested. The *native performance* -i.e. running the benchmark tool without including any virtualization layer- is used as a reference for comparison [65].

Table 5.1 shows the results of the benchmark analysis [87]. The sysbench[5] tool is used to test CPU and Disk I/O performance. The results of the CPU test demonstrate an existing difference between the native and the Docker case. However, he container engine introduces a negligible impact in terms of CPU performance, with a percentage difference in the order of 2.67%.

To test the Memory I/O performance, the Unix command *mbw*[6] has been used. It determines the available memory bandwidth by copying large arrays of data in memory, and performing three different tests (memcpy, dumb, and mcblock). Similarly to the CPU case, native and container performance can be considered comparable, with a max percentage difference of 6.04% during the memcpy test. In the Disk I/O evaluation, the benchmark is set to execute random read/write operation. A performance degradation of Docker compared to the native case can be observed in the results. This difference remains in the order of roughly 10%.

TABLE 5.1: Gateway for the CoT - benchmark results.

	CPU	**Memory**			**Disk I/O**	
	Execution Time (seconds)	*memcpy (MiB/s)*	*dumb (MiB/s)*	*mcblock (MiB/s)*	*Read (MB)*	*Write (MB)*
Native	434.074	598.22	70.93	601.55	123.25	82.172
Docker	446	562.05	70.43	570.51	107.062	74.719

[5] http://manpages.ubuntu.com/manpages/wily/en/man1/sysbench.1.html

[6] http://manpages.ubuntu.com/manpages/wily/en/man1/mbw.1.html

5.4 Design of the gateway for VITAL-OS

In this Section, the design of a Gateway for the Cloud of Things is described in order to connect a Sensor Network to VITAL-OS. The scenario is the monitoring in a Smart Building environment. In order to make possible this connection, the gateway has to communicate with the IoT Data Adapter module of the VITAL-OS and to act as a sink for the SN.

Figure 5.6 shows some examples of interaction between the aforementioned players.

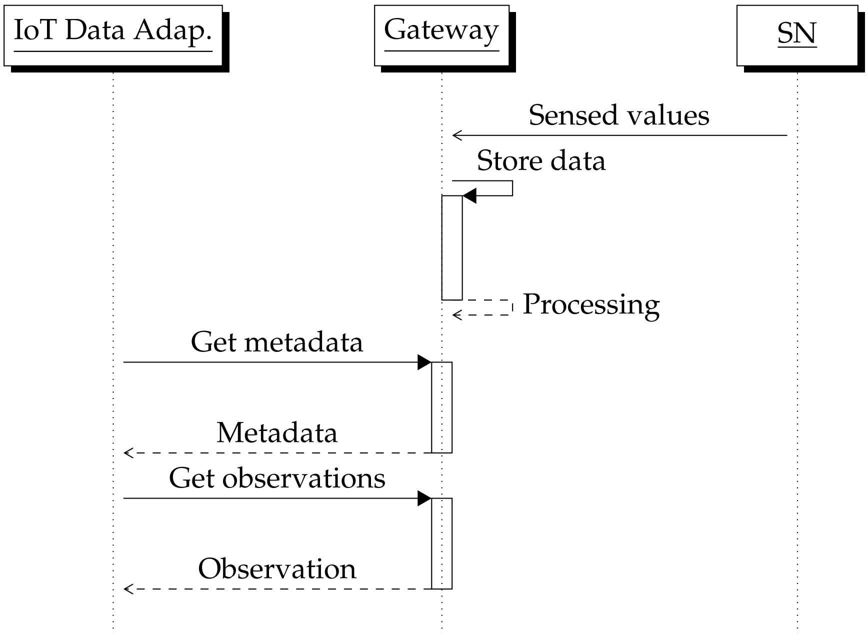

FIGURE 5.6: Gateway for the CoT - interaction with the VITAL-OS.

FIGURE 5.7: Maxfor sensor node. (source http://www.maxfor.co.kr)

In order to sense the physical environment, Maxfor nodes (Figure 5.7) have been chosen. A node embeds a MSP430 as CPU and CC2420 as radio frequency module, and it is integrated with temperature and light sensors (Table 5.2).

The sensor nodes use Contiki-OS and in particular their firmware is flashed with eCACHACA, an extended version of the ranking mechanism CACHACA described in Chapter 4.

TABLE 5.2: Sensor node specifications.

Parameter	*Specification*
CPU	MSP430
RF Chip	Texas Instruments ®CC2420
Frequency Band	2.4 GHz – 2.485 GHz
Transfer Rate	250 Kbps
RF Power	-25 dBm – 0 dBm
Range	120m [outdoor]; 20-30m [indoor]
Sensor Temperature & Humidity	Sensirion ®SHT11
Sensor Light	600 nm peak

eCACHACA borrows its main features from its "ancestor" -nodes describe their services according to a standardized format, etc.-. The novelty introduced regards the frame format; as shown in Figure 5.8, when using eCACHACA, a node advertises also the measured value. This mechanism allows the gateway to have all the information required to publish sensor data to VITAL-OS.

FIGURE 5.8: Frame format in eCACHACA.

To be part of the VITAL-OS, the gateway provides and exposes a PPI implementation. Through that implementation, it is possible to retrieve:

- Information about the system (e.g., its status).
- Information about the services exposed and how to access them.
- Information about the sensors managed and what they observe.
- Observations made by the sensors.

According to VITAL specifications [102], the PPI is defined as a set of RESTful web services. Listing 5.1 shows an example of a response to the GET SYSTEM METADATA primitive, in which the gateway exposes information about the network (e.g., its type and description), as well as a list of the available services and the managed sensors.

LISTING 5.1: PPI - Get system metadata.

```
{
  "@context": "http://vital-iot.eu/contexts/system.jsonld",
  "id": "http://example.com/rpi2_ppi",
  "type": "vital:VitalSystem",
  "name": "RPi2 PPI Implementation",
  "description": "VITAL compliant system to retrieve data coming
      from RPi2",
```

```
  "services": [
    "http://example.com/rpi2_ppi/observation"
  ],
  "sensors": [
    "http://example.com/rpi2-ppi/sensor/95",
    "http://example.com/rpi2-ppi/sensor/3",
    "http://example.com/rpi2-ppi/sensor/20",
    "http://example.com/rpi2-ppi/sensor/44"
  ]
}
```

To summarize, in this circumstance, the main tasks of the gateway are:

- Managing the sensor network.
- Formatting the information received from sensor nodes based on the VITAL ontology.
- Storing information into a local database.
- Exposing a PPI implementation via the web.

In order to deal with the aforementioned requirements, as shown in Figure 5.9, the gateways has be designed by using three main Docker images:

- A web server to expose services to VITAL-OS and in particular, **WildFly**[7] an application server written in Java, which runs on multiple platforms.
- A search server in which all sensor data is stored. **Elasticsearch**[8] has been chosen because it provides a distributed search engine with an HTTP web interface and schema-free JSON documents.
- A third component that communicates with the Sensor Networks running eCACHACA.

5.4.1 Performance

To evaluate the performance of the gateway and eCACHACA, experiments have been run on FIT IoT-lab. The following metrics (measured at the gateway) are used: *(i)* the number of neighbors discovered, *(ii)* the time required, and *(iii)* the Physical confidence. In order to study the behavior of the network, the number of nodes is varied from 10 to 90 -considered sufficient for many Smart City applications by [24]-.

Figure 5.10 shows the percentage of NEIGHBORS DISCOVERED by the gateway as a function of the NUMBER OF NODES. With 10 nodes deployed, the gateway discovers all of them; while when we increase the number of

[7] http://wildfly.org
[8] https://www.elastic.co

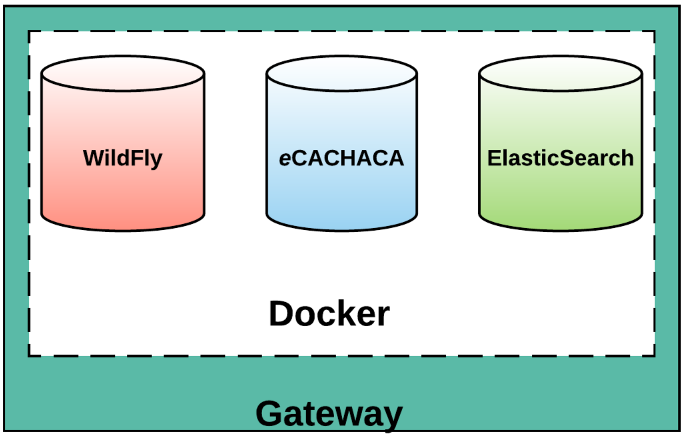

FIGURE 5.9: Gateway for VITAL-OS - architecture.

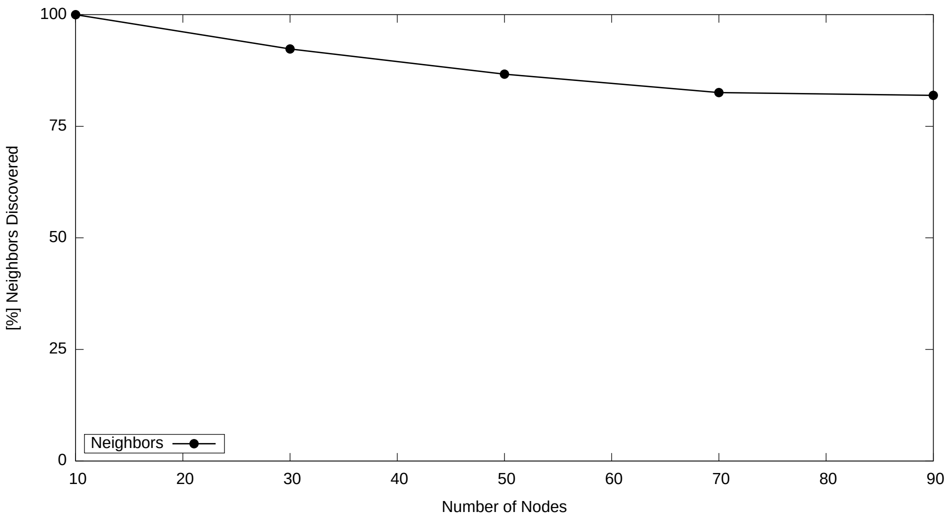

FIGURE 5.10: Gateway for VITAL-OS - Number of Nodes vs. Neighbors Discovered.

nodes, this performance downgrades but it is still acceptable, indeed 80% of nodes is discovered.

The time required to discover those nodes is represented in Figure 5.11. When the network is not dense (10 nodes), the discovery process is fast; all the nodes are discovered in less than 15 seconds. When increasing the number of nodes, the gateway can discover the 80% of them in less than 70 seconds. Moreover, after 70 seconds the process is stable, the gateway will not discover more nodes.

The last analysis (Figure 5.12) provides information about the PHYSICAL CONFIDENCE. When 10 nodes are deployed, the physical aspects measured at the gateway are more close to "Excellent". While, when increasing the number of nodes, the Physical confidence is "Good". This is due to the interference that possibly occurs when the network is more dense.

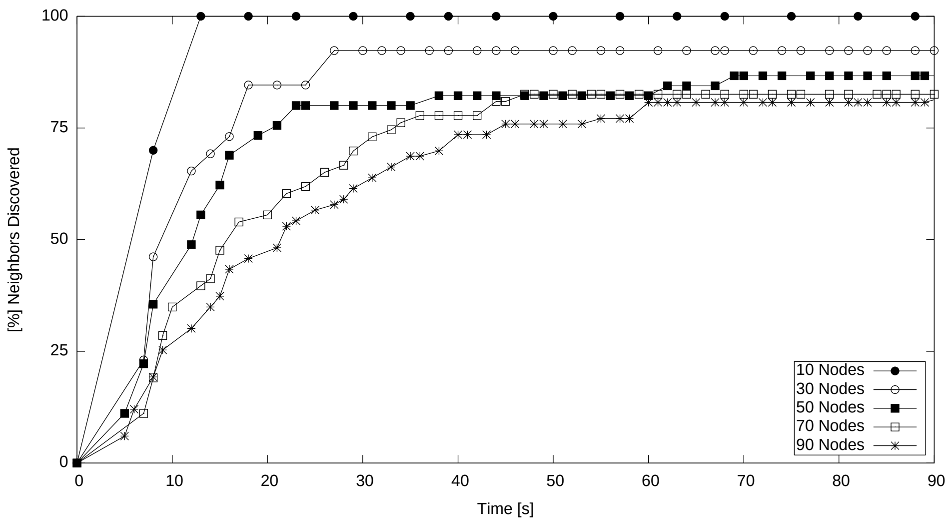

FIGURE 5.11: Gateway for VITAL-OS - Neighbors Discovered - temporal trend.

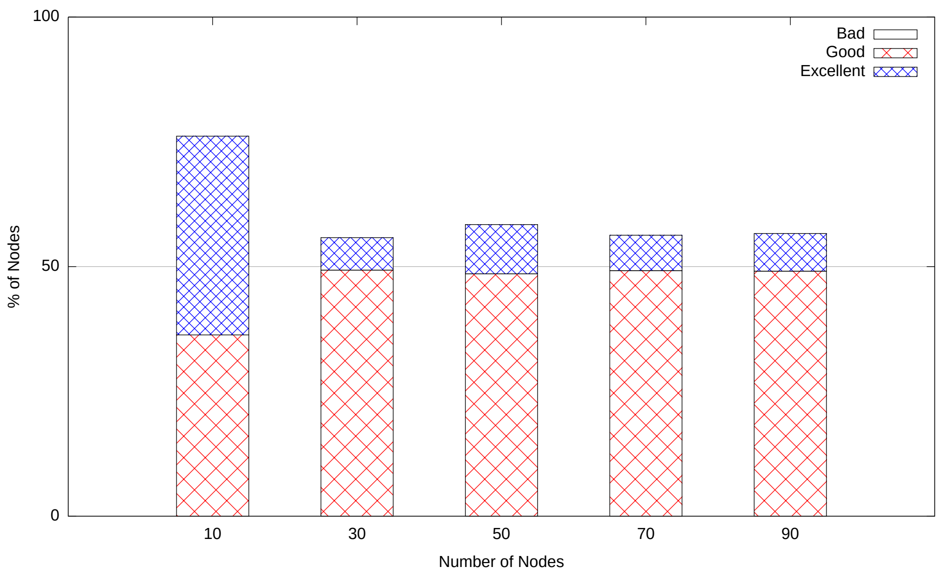

FIGURE 5.12: Gateway for VITAL-OS - Number of Nodes vs. Physical Confidence.

5.4.2 Using VITAL-OS

VITAL-OS provides a development tool that integrates all VITAL-OS functionality and makes them accessible to Smart City application developers. The fact that all functionalities are exposed via virtualized interfaces (i.e. RESTful web services) facilitates the task of integrating them into a single tool.

The development tool is based on Node-RED [9], an open-source tool for wiring the IoT that we have extended with nodes specific to the purposes and the needs of the VITAL-OS, as shown in Figure 5.13.

[9] http://nodered.org

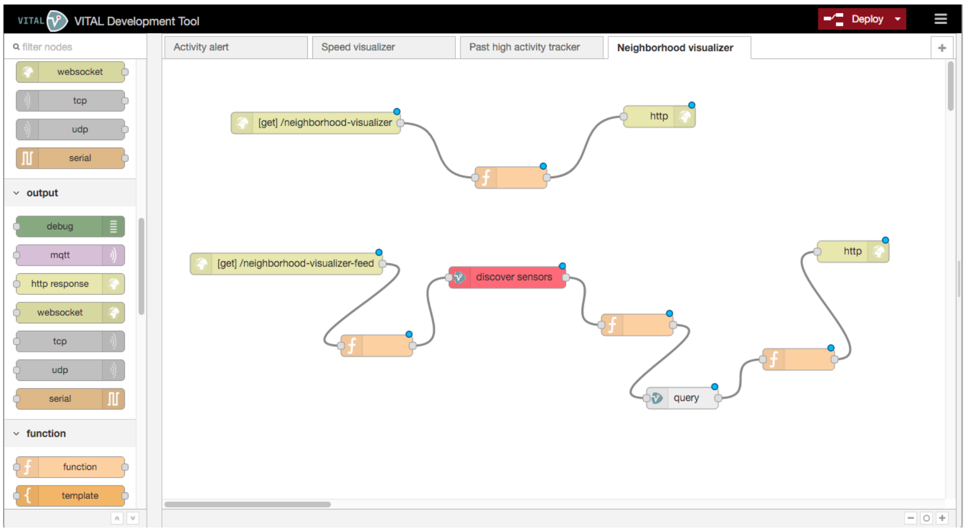

FIGURE 5.13: The VITAL-OS development tool.

The development tool is used by developers that want to build and deploy Smart City applications that involve multiple IoT platforms, architectures and business contexts. For that purpose, the tool enables them to access and compose the following VITAL-OS functionality:

- ICOs and Services Discovery.
- Complex Event Processing.
- Filtering.
- IoT System, ICOs, data stream, security, configuration, and component management.
- Business Process Management.

The developers can even use the tool to directly access PPI primitive implementations, like the one provided for the SN. Based on the above and in the context of this example, a developer can use the VITAL-OS development tool to build a website where users will be able to find out how each sensor has classified its neighbors.

5.5 Conclusion

In this Chapter a gateway for the Cloud of Things has been introduced. The gateway is capable to manage semantic-like things -which may use different radio technologies- and to act as end-point for the dynamic presentation of sensed data to consumer applications and users.

The proposed architecture makes the gateway capable to deal with different IoT scenarios and technologies. Thanks to emerging virtualization techniques the gateway guarantees, indeed, a lightweight and dense deployment of services. Moreover, even with limited computation resources, the gateway can perform operations -filtering, compression, aggregation, etc.- that affect positively the network throughput.

Finally, in order to validate the proposal, the gateway has been designed in order to communicate, from one side, with the VITAL-OS and on the other, with eCACHACA.

Regarding the future works, different are the enhancements that can be studied. For example, it could be interesting to design an algorithm running on the gateway itself capable to select the best resources for a specific application (e.g., monitoring of Points of Interest). Moreover, the energy consumption of the network is a metric that can be improved by introducing algorithms capable to predict data produced by each sensor [31], avoiding therefore nodes to access continuously the channel, and therefore improving the energy consumption.

Other investigations can be conducted in order to test alternative technologies to Docker such as CoreOS[10], and alternative hardware to Raspberry such as BeagleBone[11], ODROID[12], and so forth.

[10] https://coreos.com
[11] http://beagleboard.org/bone
[12] http://www.hardkernel.com

Chapter 6

Conclusions and Outlooks

6.1 Conclusions

The Smart City concept gained, in the last few years, an extensive attention from both academia and industry. The reasons behind this interest are attributable to the real need to intervene in the urban environment and make it more livable. With the continuous growth of the urban population indeed, new challenges have to be faced -i.e., traffic congestion, air pollution, waste management, etc.-.

As it is already stated, in this context the role of Information and Communication Technologies, and especially the Internet of Things, is crucial as an enabler of the integration required by the Smart City vision. Indeed, even if many definitions of Smart City exist in literature, the need of integration, between all its stakeholders, is a common concept.

Anyway, looking at the current status, the proposed approaches are more driven by solving specif problems (e.g., environmental monitoring, traffic monitoring etc.). Thus, those solutions can be considered standalone, based on protocols and standards that are vertically integrated. As a consequence, the IoT landscape results highly fragmented and the realization of the Smart City vision as *System of Systems* seems unlikely.

To bridge the gap between those different IoT ecosystems, in this Thesis we have proposed an evolution of the Internet of Things towards the Cloud of Things. At the basis of this progression there are Semantic and Cloud technologies. The first ones, are recognized as good enablers in the complex process of integration of heterogeneous data-sources; at the same time, applying Cloud computing models to *things* already deployed in the urban environment, will make possible to exploit all the capabilities offered by those devices, avoiding to install new ones, while assuring scalability, availability, and so forth. The VITAL operating system for Smart Cities, is an European Commission funded project that embraces the Cloud of Things philosophy. Its objective is to offer tools that can monitor, visualize, and control all the operations of a city.

In this context, where billions of Internet-Connected Objects are available, it is important to have mechanisms providing the resources that better suit business criteria defined by users. To deal with this challenge, a contribution of the Dissertation regards the development of the *VITAL ICOs & Services Discovery*. It is horizontally integrated in the platform and is responsible for discovering ICOs, Systems, and Services. The discovery process is driven by properties such as the position of the ICO, its type of mobility and connectivity, and its observation capabilities.

The VITAL ICOs & Services Discovery is designed to deal with *out-network* tasks. However, the semantic concepts used in VITAL, can be applied also *in-network*, when dealing directly with the building and the maintenance of the network itself. In this regard, we also proposed the *CACHACA* algorithm. By running CACHACA, it is possible to evaluate and classify the neighborhood and the available services for each node. In order to estimate the pertinence of neighbors and services, it leverages on the flexibility of the fuzzy logic and on its capacity to handle, without high computation costs, imprecise and incomplete data. CACHACA has been evaluated both with simulation and experimentation. Results show that it can obtain good results compared to the ideal scenario in terms of Neighbors and Services discovered.

Focusing on the horizontal unification of different data-sources and the need to bring processing capabilities closer to the network, the last contribution of this Thesis targets the design of a gateway for the Cloud of Things. The proposed architecture includes features that take advantage of the lightweight and versatile container-based virtualization -which introduces a negligible impact in terms of performance- and the use of semantic techniques to enable the horizontal unification of different *objects*. The gateway is designed to deal within different IoT scenarios in which services may be instantiated only temporarily and in an efficient way. To validate the proposal, we implemented and run experimentation on real hardware, and we connected it to the VITAL-OS, bridging the contributions of this Dissertation.

6.2 Outlooks

In this Thesis, we have focused on different technological aspects of the Smart City vision.

Firstly, we introduced the VITAL project that has the ambitious objective to be an operating system for smart cities. Many are the initiatives in this direction [90, 17], strengthening the need to integrate and use all data-sources available in the urban environment, in order to implement **complete** and **innovative** solutions, services, applications and therefore improve sustainability and livability. On the other hand, this operation requires an important social effort; citizens, but also companies and authorities, indeed, need to be ready to share relevant information, and this is not an easy process. It is then important to create good and fair cultural and business models around those concepts. From the technological point of view, the VITAL platform needs to improve its performances in terms of scalability and also to guarantee more privacy to data-producers and data-consumers.

Regarding the gateway introduced in Chapter 5, it can suit in different Smart City scenarios, especially in those where different devices use different technologies, like for example Smart Building, Smart Factory, etc. In this work, the gateway has been designed to communicate -via Ethernet and/or Wi-Fi- with the VITAL-OS, but it can offer its services to the Internet in general. The gateway can be enhanced by introducing other communication technologies such as LoRa [59], Sigfox [101], or 4G.

Concerning the proposed CACHACA algorithm, in a world that is increasingly populated by *things*, it is important to make them aware about what they can do, and how they can do it. Often those kind of operations are centralized, while in this work, we implemented a distributed solution, highlighting the self-sufficiency aspect of those devices. Due to the technological fragmentation -different radio standards and protocols- CACHACA cannot be used for cross-standard communications. However, over the past few years, the IP is proposed as unifying network layer, therefore an implementation of CACHACA could be considered at this layer.

6.3 Personal conclusions

Dealing with the development of complex systems is never an easy task; and it gets even harder when this progress involves humans and the way they live. This is what happens when we try to define and design a Smart City. Nevertheless the topic is hot -everyone (politicians, industries, scientists, citizens, etc.) talks about it- it is difficult to converge on a common vision about how and what it will be.

What is clear is that the City, throughout its history, has always been the core of aggregation and socialization among people, and its role should remain unchanged.

Nowadays, we are proposing the next Cities as Smart Systems, where technologies will connect people and all the things around. Anyway, this evolution should focus on the improvement of the quality of life in the urban environment, and this process should be **fair**.

Many indeed, are the concerns about this social aspect. In India, for example, the Prime Minister Narendra Modi launched in 2015 the Smart Cities Mission[1], with involves 100 cities and it is founded with 480 billion rupees ($ 7.1 billion). This huge amount of money, attracted many foreign companies and arousing citizens to ask questions such as: *will smart cities have any space for the poor? Or the benefits will be grabbed by the well-to-do sections and the poor will get left out of the experiment?*

[1] http://smartcities.gov.in

An unhappy case, in this circumstance, is happening in San Francisco (California, United States). According to the "San Francisco 2.0" documentary[2], directed by Alexandra Pelosi, the city is changing its heart and soul. Young members of the tech elite are indeed, flocking to the West Coast to make their fortunes, and this new wealth is forcing San Francisco to reinvent itself. The gap between rich and poor is constantly growing, driving an increasing number of evictions[3], and therefore homeless.

It is therefore essential to learn from those lessons, and try to use technologies to develop a fairest world. Regarding the Smart City context, technologies should allow a city to run itself efficiently and to provide solutions to various problems such as pollution, water supply, electricity, etc.

The initiatives and solutions to address those problems, are already available and based on different standards and protocols. In this fragmented landscape, it will be difficult to have a unique competitor. Therefore the development of platforms that collect and manage different things is necessary. Data gathered from those heterogeneous data-sources can be then processed, by using data mining tools, in order to obtain useful information. The role of Semantic technologies in this process is crucial as enabler of the homogenization of those resources.

At the same time, the design of sophisticated algorithms that provide to end-users the aimed services -and/or resources- will sign an important revolution on the field, just as Google did for the Web some years ago. Maybe even more.

Last but not least aspect that worth being mentioned is the privacy. With the increasing number of gadgets and sensors (e.g., cameras on the street, smartphones, smartwatches, etc.) that can track our lifestyle and gather personal information, it is important to have mechanisms that guarantee the respect of our privacy. Often indeed, we have the impression to live in a world similar to the one romanced by George Orwell in $Nineteen Eighty-Four$ [70], and this is something that we, all, should avoid.

[2] http://www.alexandrapelosi.com/start.php?page=10
[3] http://www.antievictionmappingproject.net/ellis.html

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- R. Petrolo, R. Morabito, V. Loscrì, and N. Mitton. "The design of the gateway for the Cloud of Things". In: *Annals of Telecommunications* (2016). DOI: 10.1007/s12243-016-0521-z
- R. Petrolo, V. Loscrì, and N. Mitton. "Towards a Smart City based on Cloud of Things, a survey on the smart city vision and paradigms". In: *Transactions on Emerging Telecommunications Technologies* (2015). DOI: 10.1002/ett.2931
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- R. Petrolo, V. Loscrì, and N. Mitton. “Cyber-Physical Objects as key elements for a Smart Cyber-City”. In: *Management of Cyber Physical Objects in the Future Internet of Things: Methods, Architectures and Applications*. Springer International Publishing, 2016, pp. 31–49